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Data to Cartography New MDE-Based Approach for Urban Satellite Image Classification

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ABSTRACT

Monitoring of the earth's surface has been significantly improved thanks to optical remote sensing by satellites such as SPOT, Landsat and Sentinel-2, which produce vast datasets. The processing of this data, often referred to as Big Data, is essential for decision-making, requiring the application of advanced algorithms to analyze changes in land cover. In the age of artificial intelligence, supervised machine learning algorithms are widely used, although their application in urban contexts remains complex. Researchers have to evaluate and tune various algorithms according to assumptions and experiments, which requires time and resources. This paper presents a meta-modeling approach for urban satellite image classification, using model-driven engineering techniques. The aim is to provide urban planners with standardized solutions for geospatial processing, promoting reusability and interoperability. Formalization includes the creation of a knowledge base and the modeling of processing chains to analyze land use.

Keywords: Urban Geospatial Analysis; Urban Planning Meta-Models; Model Driven Engineering; Machine Learning; GeoAI

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1. Introduction

In the field of urban planning [1], the growing availability of satellite data offers unprecedented opportunities for in-depth analysis of the urban environment. However, transforming this raw data into meaningful and usable information remains a major challenge. Satellite image classification, which aims to identify and categorize the different elements of the urban landscape, is a crucial step in this analysis. However, traditional classification approaches are often limited by their ability to manage the complexity and variability of urban data [2].

This article proposes a new approach to urban satellite image classification, based on model-driven engineering (MDE) [3], with the aim of standardizing and automating this process. Based on an MDE approach, this method allows the classification process to be abstractly modeled, thus facilitating its application and adaptation to the specificities of urban environments.

The MDE framework also enables a systematic and reproducible approach to classification by formalizing the steps in the process and facilitating the automation of repetitive tasks. By integrating data models and processing models into a unified framework, this approach fosters effective collaboration between urban planning experts, data specialists and geographic information system (GIS) developers [4].

The application of this approach to the classification of satellite images in urban planning aims to produce detailed and accurate urban maps, providing a solid basis for urban planning and management. By focusing on the flexibility and robustness of the classification process, this method seeks to improve the quality and reliability of the information extracted from satellite images, thereby contributing to more informed decision-making and more effective urban policies. A meta-modeling approach, based on model-driven engineering (MDE), would effectively standardize and automate the urban satellite image classification process, facilitating collaboration between urban planning experts and data specialists, while improving the quality and reliability of geospatial information for informed decision-making in urban management.

In this article, we will explore in depth the fundamental principles of model-driven engineering and their application to the classification of satellite images in urban planning. We will introduce a generic metamodel, designed to represent in an abstract way the different aspects of the classification process, from data pre-processing to the production of final urban maps. This metamodel will serve as a conceptual framework for understanding how the different components of the system interact and articulate to achieve accurate and meaningful classification of satellite imagery. In addition, we will examine the specific tools and techniques used in this approach, highlighting their role in modeling the classification processes and their contribution to improving the results obtained. Finally, we will discuss the challenges and opportunities associated with the application of model-driven engineering to the classification of satellite images in urban planning, exploring the prospects for this promising approach in the field of spatial analysis and urban planning. The objective of this paper is to provide a new approach to urban geospatial analysis based on model-driven engineering.

The article is organized as follows: Section 2 covers related work pertinent to our topic; Section 3 delves into model-driven engineering; Section 4 outlines the key components and various applications of urban satellite image classification; Section 5 introduces our proposed generic meta-model approach for urban geospatial analysis; Section 6 discusses the results of our study; and finally, Section 7 provides the conclusion.

2. Related Work

These related works illustrate the diversity of approaches and techniques used in the field of satellite image classification in urban planning [5, 6], reflecting the growing importance of this discipline for the planning and management of cities. The rapid expansion of urbanization and current environmental challenges require precise tools and reliable data to analyze the evolution of urban areas and the spatial dynamics of cities. In this context, satellite image classification [7] is emerging as an essential technique, offering the possibility of extracting detailed information from high-resolution aerial images.

Indeed, many researchers have worked on satellite image classification, particularly in the field of urban planning. Consequently, in our previous work [8–12], we provided specific evaluations and comparison studies of different geospatial image processing models and algorithms for analyzing urban planning. These comparative studies, as well as the evaluations made by these authors [13–15] on the same field of satellite image classification in urban areas have led to the definition of the fundamental concepts and essential characteristics of satellite image processing [16] and analysis in urban areas. The classification of satellite images for urban planning requires a global approach, including data collection, data pre-processing [17], feature extraction, the development of classification models, and the evaluation of results, as well as their visualization.

Among supervised machine learning algorithms, we will provide an overview of each available classifier or method:

Support vector machines (SVMs) [18] are a family of machine learning algorithms for solving classification, regression, or anomaly detection problems. These algorithms stand out for their sound theoretical guarantees, high flexibility, and ease of use, even for users with little knowledge of data mining [19]. Their aim is to separate data into classes using the simplest possible boundary, while maximizing the distance between this boundary and the various data groups, known as the "margin".

Minimum distance classification [14] is a special case of the maximum likelihood method. The classifier calculates the distance of each pixel to the mean of each class using several standard deviations in the direction of the pixel, then assigns the pixel to the class with the smallest distance value, according to the Mahalanobis distance.

Decision tree algorithms [20] create a tree structure by learning decision rules from the training data and according to the parameters used to determine a pixel's class. Leaves represent classes, while intermediate nodes represent attributes or features. These algorithms are well suited to regression and classification problems. There are many different types of decision trees, such as CART, C4.5, C5.0, and ID3. They can handle different types of data, whether non-linear, numerical or categorical, and are robust to missing values.

The Random Forest method [20] constructs several decision trees. It is one of the most popular algorithms due to its accuracy, simplicity and flexibility. It can be used for classification and regression tasks, and its non-linear nature makes it suitable for a wide variety of data and situations. This algorithm is called a "forest" because it generates several decision trees, whose predictions are then combined to guarantee better accuracy. Unlike a single decision tree, which gives a single result, the forest ensures more accurate predictions thanks to a collective approach. In addition, Random Forest introduces randomness by selecting a random subset of features at each step.

Gradient Tree Boosting (GTB) [21] is a machine learning technique used for classification and regression tasks. It is particularly popular with data scientists for its accuracy and speed, especially when dealing with large datasets (big data).

In this paper, we propose a unified abstract implementation by proposing a generic meta-model for satellite image classification applied to urban planning. The main objective of this universal meta-model is to provide urban planners with standardized and consistent solutions for the classification of geospatial data in the context of urban planning.

3. Model Driven Engineering

Model-Driven Engineering (MDE) [22] is a methodology that transforms the development of software systems by placing models at the heart of the design and implementation process. Unlike traditional approaches, which focus primarily on manual coding and direct management of source code, model-driven engineering emphasizes the creation, transformation and use of abstract models to represent various aspects of the system at different levels of abstraction. This approach is supported by Model-Driven Architecture (MDA), a framework proposed by the Object Management Group (OMG), which standardizes the use of models to guide the development of software systems. **Figure 1** shows the OMG pyramid.

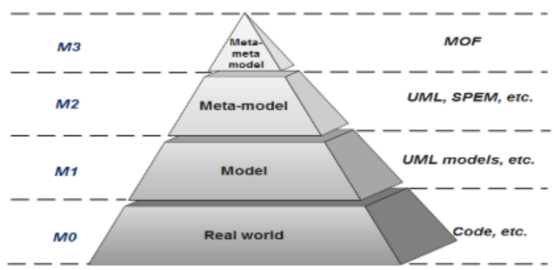

Figure 1. OMG modeling pyramid [22].

The models used in MDE, and more specifically in MDA, are abstract, formalized representations of system elements, including data flow diagrams, behavior models, software architectures and component specifications. These models are generally created using standardized modelling languages, such as the Unified Modeling Language (UML), to capture and describe system requirements, structure and behaviors in a consistent and understandable way. In the context of MDA [23], models are often classified into two main categories: Platform-Independent Models (PIMs) [3] and Platform-Specific Models (PSMs). PIMs are abstract descriptions of systems without considering the particularities of the technological platforms, whereas PSMs detail these systems by considering the technical specificities of the platforms on which they will be deployed. **Figure 2** shows the levels of the MDA model.

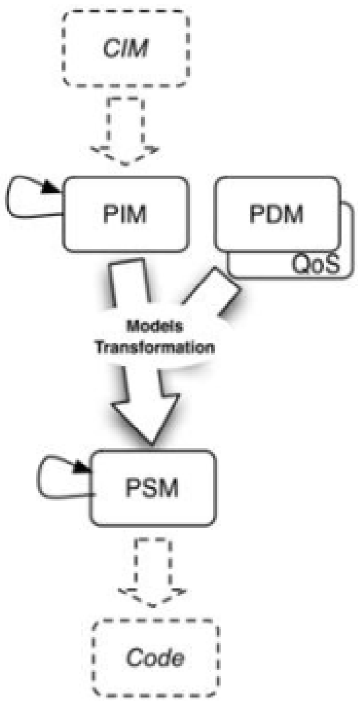

Figure 2. MDA model levels [3].

One of the key aspects of model-driven engineering is the automatic transformation of models, making it possible to move from one level of abstraction to another in a systematic way, often using code generation tools. For example, a PIM describing functional requirements can be transformed into a detailed PSM [22], which can then be used to automatically generate some or all the source code. This automation reduces the risk of human error, improves consistency between the different phases of development and speeds up the overall development process.

The benefits of model-driven engineering are numerous. Firstly, it improves communication between the various project stakeholders, using visual models that are easily understood even by non-technical people. Secondly, it enables better management of complexity by dividing the system into modular models and facilitating their integration. Thirdly, it improves the maintainability and scalability of systems by making models easy to modify and adapt to new requirements.

In the field of urban planning, and more specifically for the classification of urban satellite images, model-driven engineering, and in particular MDA [24], can be extremely beneficial. It can be used to model the various stages in the image processing process, from data collection to pre-processing, feature extraction and final classification. By using PIMs to represent these steps in an abstract way, it is possible to create image processing algorithms that are both flexible and extensible, tailored to the specific needs of urban planning.

4. Urban Satellite Image Classification

Urban geospatial analysis is a field of research and application that uses geospatial technologies to study, model and manage urban spaces. By combining geographic data with advanced analysis techniques, it offers valuable insights into the structure, dynamics and evolution of urban environments. **Figure 3** shows the proposed pipeline for classifying urban satellite images using machine learning algorithms.

4.1. Key Components of Urban Satellite Image Classification

Key components of urban geospatial analysis include:

- Data Collection
  Data collection, involving the acquisition of satellite imagery as well as the integration of complementary data such as LiDAR and GIS.
- Data Pre-Processing and Feature Extraction
  Data pre-processing, which involves cleaning, standardizing and merging data from different sources, ensures that the data is error-free, consistent and integrated. Feature extraction, using techniques such as image segmentation and object detection, enables significant areas to be analyzed in more detail, and

specific objects such as buildings, roads and green spaces to be identified and classified.

- Modelling and Classification
  Modelling and classification use sophisticated algorithms, such as neural networks, random forests and support vector machines, to classify different urban features and establish predictive models based on historical and current data.
- Analysis and Visualization
  Analysis and visualization, through thematic mapping and 3D visualization, create visual representations that highlight specific features or trends in urban data, facilitating a better understanding of spatial structure.

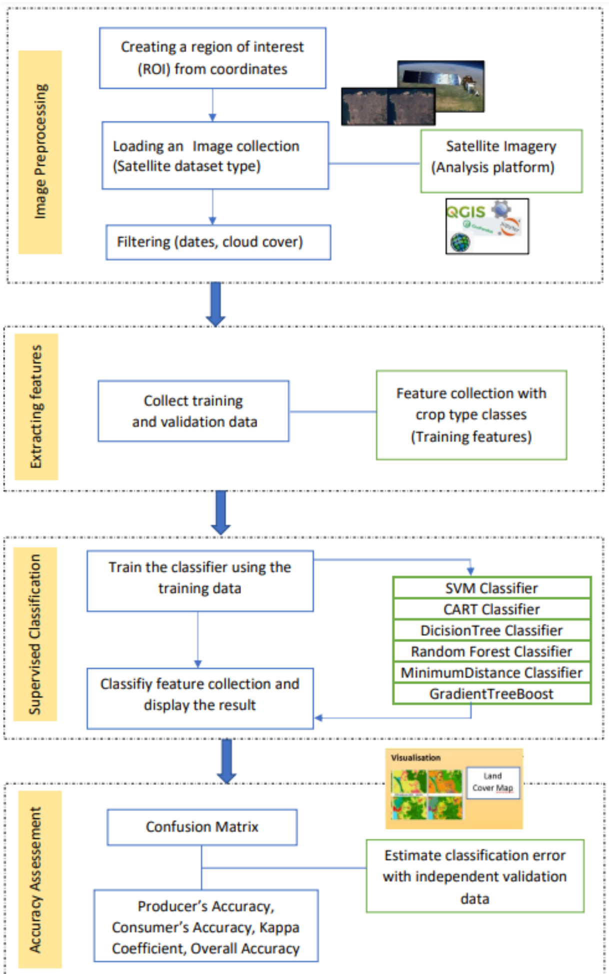

Figure 3. Proposed pipeline for classifying urban satellite images using machine learning algorithms.

4.2. Applications of Urban Satellite Image Classification

The applications of urban geospatial analysis are vast and varied, encompassing urban planning, risk and disaster management, environmental monitoring and sustainable development. These applications help to design and manage urban infrastructure, assess areas at risk from natural disasters, monitor changes in land cover and green spaces, and support sustainable development initiatives by providing analyses of energy efficiency, greenhouse gas emissions and the ecological footprint of urban areas.

By integrating advanced data collection, modelling and visualization technologies, urban geospatial analysis enables city planners, policymakers and researchers to make more informed decisions to create more resilient, efficient and sustainable cities.

5. Proposal for a Generic Meta-Model for Urban Geospatial Classification

In this article, after presenting the basic principles of model-driven engineering and the MDA approach in the previous section, we will propose a generic meta-model for the classification of satellite images applied to urban planning. This meta-model aims to provide a standardized and unified framework for structuring geospatial data, facilitating the integration of different classification methodologies and improving the accuracy and consistency of the urban maps generated. The main objective is to provide urban planners and researchers with a powerful tool for analyzing and managing the spatial dynamics of urban environments more effectively and rigorously. **Figure 4** presents our proposal for a generic meta-model for satellite image classification applied to urban planning.

This approach is used in a variety of sectors, including urban planning, environmental management, precision agriculture and the monitoring of urban transformations. It offers users the ability to manage vast volumes of satellite data, facilitating the production of relevant information for informed decision-making. This metamodel represents a complex software architecture for processing and classifying satellite images, particularly regarding urbanization and land cover types. Here is a detailed explanation of the various key components:

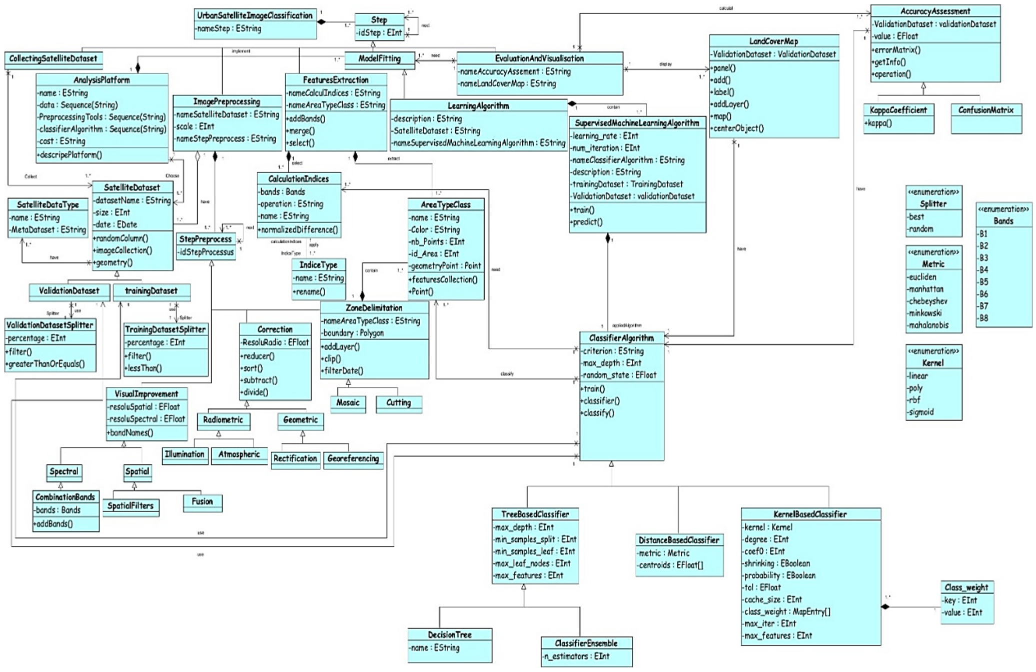

Figure 4. Proposal for a generic meta-model of urban geospatial classification.

- Satellite Data Management: The system includes modules for collecting, validating and processing satellite datasets. This includes functionality for processing and preparing data for analysis, such as resizing, radiometric and geometric correction, as well as visual enhancement.
- Feature Extraction: Image features are extracted to aid classification. This can include indices calculated from the spectral bands of the images.
- Machine Learning: Uses supervised learning algorithms [25, 26] to train models capable of classifying images into different land cover categories or land use types.
- Accuracy Assessment: Includes mechanisms to assess the accuracy of the classifications made, using tools such as the confusion matrix and the Kappa coefficient to measure model performance.
- Visualization of Results: Provides functionality to visualize the land cover maps generated, facilitating interpretation and subsequent use of the data.

In the context of satellite image management and analysis, the proposed metamodel provides a systematic structure for the advanced classification of urban areas and land cover from remotely sensed data. The model integrates several key meta classes, each targeting specific aspects of the image processing process, from data collection to the evaluation of classification model performance.

The main class, UrbanSatelliteImageClassification, encapsulates the global urban satellite image classification process. It is defined by the nameStep attribute, which identifies the various stages in the process. The abstract class Step, identified by idStep, is a generic class which is inherited by all the specific sub-classes, representing the distinct stages of the process.

The first metaclass, CollectingSatelliteDataset, is designed to manage the collection and organisation of satellite datasets. It specifies the type of data, its size and the associated metadata, which is crucial for preparing the ground for the subsequent processing stages. Following this stage, the ImagePreprocessing meta class plays a central role by applying radiometric and geometric corrections to improve image quality. This pre-processing is vital because it directly influences the efficiency of the classification stages.

At the heart of our system, the FeaturesExtraction metaclass is responsible for extracting relevant features from images. It uses advanced methods to calculate various indices from spectral bands, providing crucial data for classification algorithms. This extraction is adapted to capture the nuances of urban areas, enabling more accurate and nuanced classification.

The CalculationIndices metaclass is central to the calculation of indices from spectral bands, with attributes such as bands, operation, and name. It also includes the normalizedDifference() method for performing specific calculations. IndiceType, with the 'name' attribute and the rename () method, describes the different types of indices used in calculations. The AreaTypeClass metaclass classifies areas by type, with attributes such as name, color, idArea, nbPoints, and geometryPoint, allowing detailed characterisation of the areas analysed.

The LearningAlgorithm metaclass covers the development and training of machine learning models, with a subclass dedicated to supervised learning algorithms. These models are trained using extracted features to predict land cover classes. The methods in this metaclass, such as Train and Predict, facilitate not only the training of models but also their rigorous evaluation.

The SupervisedMachineLearningAlgorithm class, defined by attributes such as learning_rate, max_iteration, criterion, and 'description', includes train () and predict () methods, and is linked to the TrainingDataset and ValidationDataset metaclasses for managing training and validation datasets. ClassifierAlgorithm describes classification algorithms with attributes such as 'criterion', max_depth, and random_state, and the train (), classifier (), and classify () methods crucial to the classification process.

The metaclasses, ValidationDataset and TrainingDataset, are defined by percentage and filter attributes, allowing selection criteria for datasets to be specified for model validation and training. LandCoverMap manages land cover maps, with attributes and methods for adding, removing, and manipulating map layers, providing tools for visualizing results.

The Correction metaclass includes methods for reducing, sorting, subtracting and dividing data, defined by the resolRatio attribute, while VisualImprovement improves the visual quality of data with resolSpatial and resolSpectral attributes.

The AccuracyAssessment metaclass is crucial for assessing the accuracy of the classifications produced by the models. It uses statistical tools such as the Kappa coefficient and the confusion matrix to measure and visualize model performance. The importance of this metaclass lies in its ability to provide an objective assessment of the results, enabling models to be continually refined to achieve optimum performance.

The metaclass, ZoneDelimitation, delimits areas by type, with attributes such as nameAreaTypeClass and boundary, and methods for adding layers, slicing and filtering by date. CombinationBands manages spectral band combinations with the 'bands' attribute and addBands() method, making it easy to integrate different bands for analysis.

The metaclass, DecisionTree, defined by the name attribute, and Geometric, covering geometric aspects such as rectification and georeferencing, as well as Radiometric, including spatial and spectral aspects of image enhancement, are essential for specific corrections and improvements. ClassifierEnsemble combines multiple classifiers with the n_estimators attribute, providing a robust approach to improving model performance.

The metaclass, TreeBasedClassifier, is defined by attributes such as max_depth, min_samples_split, 'min_samples_leaf', and 'max_features', while DistanceBasedClassifier uses attributes such as metric and centroids. 'KernelBasedClassifier' includes attributes to handle various aspects of kernel-based classifiers, such as kernel, degree, coef0, shrinking, probability, tol, cache_size, max_iter, and max_features.

Enumerations include Splitter defining values such as best and random, Bands including B1 to B8, Metric containing values such as euclidean, manhattan, chebyshev, minkowski, and mahalanobis, and Kernel defining linear, poly, rbf, and sigmoid kernels.

The practical application of the generic metamodel to the classification of urban satellite images is based on a modular, flexible structure that enables the classification process to be adapted to different contexts, while guaranteeing standardized methods. This metamodel formalizes the main stages in satellite image processing, such as data acquisition, preprocessing (radiometric correction, geo-referencing), segmentation, feature extraction and finally the actual classification. Each step is represented in an abstract way, enabling modularity and reuse in different urban environments. A key aspect of this approach is the parameterization of algorithms. The metamodel can be used to define standard parameter sets applicable to various supervised classification algorithms such as decision trees, support vector machines or random forests. Users can adjust these parameters according to the specific characteristics of the images and urban classes to be identified, such as built-up areas, vegetation or roads. In addition, this framework enables the creation of automated processing chains. Once the data have been pre-processed, the metamodel can apply the defined classification algorithms without human intervention, generating results quickly and efficiently. This generic metamodel also promotes interoperability and process reuse between the various players involved in urban planning, such as urban planners, geomatics experts and data scientists. It provides a common framework for sharing and exchanging processing models, facilitating application to various projects and types of satellite data, such as Landsat or Sentinel. Finally, it enables the integration of feedback mechanisms to continuously refine classification results by adjusting models according to observed performance. This approach guarantees not only greater efficiency in image processing, but also greater precision in extracting the geospatial information essential for decision-making in urban planning and management.

In summary, this metamodel represents a significant advance for satellite image classification, particularly in urban contexts where accuracy and reliability are paramount. Its modular structure and integrated evaluation capabilities make it particularly well suited to the challenges posed by the vast datasets characteristic of Earth observation. The design of this system provides a robust platform for future research and development in the field of remote sensing, promising to push back the frontiers of satellite technology in the service of urban planning and environmental management.

6. Discussion and Perspective

The research described in this article introduces a novel approach to the classification of urban satellite images, based on Model Driven Engineering (MDE). This discussion section will look in more detail at the results obtained, the challenges encountered, the practical implications, and the prospects for this approach.

The application of MDE to the classification of satellite images has made it possible to structure the process into several well-defined stages, each capturing a specific aspect of geospatial analysis. The proposed meta-model has demonstrated its effectiveness by integrating various essential components such as data collection, pre-processing, feature extraction, classification and result visualization. This structuring not only improved the consistency of the workflow, but also facilitated the automation of repetitive tasks, reducing the risk of human error and increasing overall efficiency. The results show that using abstract models to manage the complexity of geospatial data and classification algorithms is beneficial. The meta-model has helped to standardize processes, making classification methodologies more transparent and reproducible. Urban planners and data analysts have been able to use this framework to formalize and structure their analyses, which has led to a significant improvement in the accuracy of the urban maps generated.

Despite the successes achieved, several challenges were encountered during this research. Firstly, the variability and complexity of urban environments pose significant challenges for the classification of satellite images. Urban structures can vary considerably from one region to another, requiring flexible and adaptive models capable of handling this diversity. Creating models that are sufficiently generic to be applied to different cities while maintaining high accuracy has been a daunting task. Another major challenge was integrating different sources of geospatial data. Satellite images, LiDAR data and information from Geographic Information Systems (GIS) need to be harmonized so that they can be used together. This integration requires advanced data fusion and pre-processing techniques to ensure that the data is consistent and usable. The limitations of this study lie mainly in the generalizability of the proposed meta-model. Although the meta-model is designed to be flexible and adaptable, its application may be limited by regional specificities or by satellite data types that require further adjustments or customizations. In addition, full automation of the classification process remains a challenge, particularly for complex urban environments where satellite images present ambiguities or insufficient resolutions, which can affect classification accuracy.

The proposed approach has significant practical implications for urban planning and city management. By providing a unified and standardized framework, the meta-model enables urban planners to create accurate and detailed maps of urban areas, which are essential for informed decision-making. For example, the land cover maps produced can be used to identify areas requiring urgent intervention, plan urban infrastructure, and monitor land use changes over time. In addition, the MDE approach facilitates collaboration between the various players involved in urban planning. Urban planners, data analysts and GIS developers can work together using a common framework, improving communication and coordination of efforts. This collaboration is crucial to tackling the complex challenges posed by rapid urbanization and environmental change. The prospects for our research are promising and open several avenues for future work. An important direction for future research is the integration of more advanced machine learning techniques, such as Deep Learning and Transfer Learning. These techniques could further improve the accuracy and adaptability of models, enabling better management of dynamic changes in urban environments.

Automating model transformations between different levels of abstraction is another interesting prospect. Using the ATL (Atlas Transformation Language) to automate these processes could further reduce human error and speed up model development. In addition, the development of sophisticated tools for the automatic generation of code from PIM (Platform-Independent Models) and PSM (Platform-Specific Models) models could make the development process more efficient.

Another potential avenue of research is the exploration of interdisciplinary collaboration by integrating societal and economic perspectives into urban geospatial models. For example, involving urban planners, economists and sociologists in the modeling process could enrich analyses and make them more relevant to urban policy and sustainable development decision-making. This holistic approach could provide more comprehensive and balanced solutions to urban challenges. It would be beneficial to study the application of this meta-model to other areas of geospatial analysis, such as natural resource management, environmental monitoring and precision agriculture. The concepts and techniques developed in this research can be adapted and applied to a variety of contexts, providing powerful tools for a wide range of geospatial applications.

Finally, our research proposes an innovative approach to the classification of urban satellite images using model-driven engineering. The generic meta-model introduced provides a unified and standardized framework for structuring and analyzing urban geospatial data, thereby improving the accuracy of urban maps and facilitating collaboration between the various players involved in urban planning. The prospects for this approach are promising, with possibilities for integrating advanced machine learning techniques, automating model transformations, and interdisciplinary collaboration. By continuing to explore and develop this approach, it is possible to push back the frontiers of satellite technology in the service of urban planning and environmental management.

7. Conclusions

In this article, we used model-driven engineering (MDE) techniques to introduce a generic meta-model for an urban geospatial classification system. Our aim was to standardize concepts and harmonize previously proposed models, thereby improving the accuracy and consistency of urban maps. This framework helps urban planners and data specialists to make informed decisions, leading to better urban planning and management.

Ultimately, model-driven engineering holds great promise for improving the classification of urban satellite imagery. Despite these successes, challenges remain, such as the variability of urban environments and the integration of various sources of geospatial data.

The results of this research provide a solid foundation for future advances in making cities smarter, more sustainable and more resilient. The continuation of these research and innovation efforts will certainly play a crucial role in the development of more effective and coherent urban solutions. Future research should focus on integrating advanced machine learning techniques, automating model transformations and exploring interdisciplinary collaborations to further improve the effectiveness of this approach.

One of the main practical applications lies in the model's ability to generate detailed and accurate urban maps, facilitating the management and monitoring of urban dynamics, such as infrastructure growth or the transformation of green spaces. The metamodel also offers a scalable and reusable solution, capable of adapting to different geographical contexts and local specificities while promoting interoperability between various systems and players involved in urban management. The potential impact of this approach on the field of urban planning is significant. It streamlines processes, reduces the costs and time involved in manual data classification, and improves decision-making thanks to accurate, up-to-date geospatial information. The future integration of this approach into urban planning systems could thus contribute to more sustainable and effective urban policies.

In conclusion, the integration of MDE into urban satellite image classification offers significant potential for advancing urban planning and geospatial analysis, promising more efficient, accurate and collaborative methodologies for managing urban spaces.

Author Contributions

H.O. designed and processed the data, analyzed the proposed methods, and edited the manuscript; A.B. and A.E. analyzed, interpreted and discussed the proposed methods; M.L. revised the manuscript.

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Data Availability Statement

You'll find all my research data in scopus and researche.

Conflicts of Interest

All authors have read and agreed to the published version of the manuscript.

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