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High-Resolution Mapping of Material Stocks in Belgian Road Infrastructure: Material Efficiency Patterns, Material Recycling Potentials, and Greenhouse Gas Emissions Reduction Opportunities

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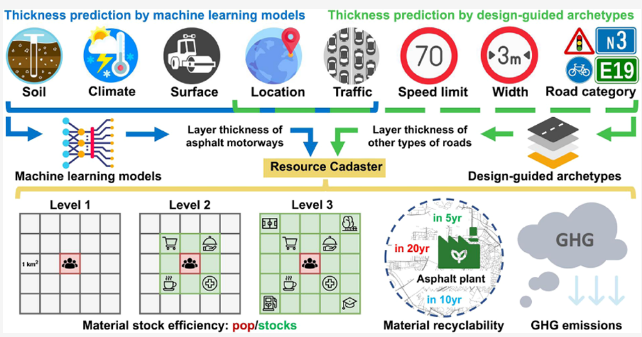

ABSTRACT: Road infrastructure is an integral part of built environment stocks, as it delivers essential social and economic services. While previous work has assessed material stocks, flows, and embodied emissions, spatially refined mapping of materials accumulated in road infrastructure can highlight hitherto underappreciated synergies between improved spatial planning, material stock efficiency, and urban mining. In this study, we mapped the materials stocked in road infrastructure across Belgium, explored the patterns of material stock efficiency and the recyclability of end-of-life road materials, and examined the greenhouse gas (GHG) emissions reductions of improving stock efficiency and recycling. We assembled data scattered across various governmental sources and crowdsourced platforms and developed a comprehensive database to warehouse locational information on road typology, layer geometry and thickness, material characteristics, traffic volume, climatic conditions, and soil conditions. Our results reveal a strong but nonlinear correlation between material stock efficiency and population density, indicating that spatial planning can reduce the required road stocks and associated GHG emissions. Urban mining potentials in road infrastructure hinge on multiple factors, such as the proximity to recycling facilities and the degradation of pavements during use. Our counterfactual analysis shows that urban road planning and reusing recycled asphalt can cut GHG emissions by up to 53 and 70%, respectively. Therefore, material-efficient road planning and improved material recycling can help realize circular economy potentials and mitigate GHG emissions moving forward.

KEYWORDS: *road infrastructure, transport, material stocks, spatially refined mapping, machine learning, material efficiency, material recycling*

1. INTRODUCTION

Built environment stocks (including building and transport infrastructure) provide essential services to fulfill basic human needs,[1,2] such as housing, workplace, mobility, and communication. Road infrastructure constitutes an integral part of built environment stocks, as it connects and shapes human settlements, ensures people's daily mobility, access to jobs, and distribution of goods, and stimulates socio-economic development of local communities.[3] However, considerable amounts of natural and financial resources, energy use, and greenhouse gas (GHG) emissions are involved in the construction, use, maintenance, and end-of-life (EoL) management of road infrastructure. The world's appetite for road construction materials is expected to grow due to the increasingly degrading road infrastructure in developed economies and the ever-increasing demand for road infrastructure in emerging economies.[4,5] According to a recent analysis,[6] providing road access to 97.5% of the global population by 2100 would lead to 16 Gt of CO_2 emissions and an investment of 3 trillion U.S. dollars.

In response to recent climate change mitigation ambitions and calls for sustainable transition, transportation and road agencies, material producers, and road engineers are increasingly embracing sustainability principles in managing their activities and urgently seeking out possible solutions to reutilize materials stocked in road infrastructure when they come to their end of life (EoL). Materials accumulated in road infrastructure—usually referred to as anthropogenic material stocks—could potentially serve as future resource providers.[5,7,8] Due to road infra-

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structure's longevity, long-term dynamics of materials stocked in road infrastructure pose critical temporal lock-in effects on (i) the volume of resources and materials consumed, (ii) the volume of EoL materials generated, and (iii) the associated energy use and GHG emissions throughout the production, use, and EoL stages. The spatial pattern of road infrastructure also plays an important role in shaping the material and energy metabolism of road infrastructure. The spatial configuration of road infrastructure can cast light on how extracted and transformed resources are redistributed and where material accumulations occur.[9]

Most recently, several studies have attempted to provide a granular understanding of materials stocked in road infrastructure.[10−18] Most of them use an archetype-based approach based on design standards and assumptions to determine material intensities and quantify material stocks. However, this precludes capturing locational heterogeneities in road properties (e.g., pavement structure, material type, layer thickness, and material composition) governed by traffic, climatic, and soil conditions. To date, only a few studies[15,16] have employed location-specific data to estimate materials stocked in road infrastructure, thanks to continuous documentation efforts of the cities or countries involved in these studies. However, location-specific data are scarce and not always available, calling for novel methods to capture locational heterogeneities in road properties. Besides, the GHG implications derivable from spatially refined stock mapping remain poorly understood.

Accurate and spatially refined mapping of materials accumulated in road infrastructure can help reveal the elusive patterns of material stock efficiency, delivering important insights on how more efficient spatial configuration can save energy and materials required for building up and maintaining road infrastructure. Moreover, the spatial knowledge of materials stocked in road infrastructure will be key for identifying urban mining opportunities, planning investments in primary and secondary operations, anticipating potential logistical constraints of waste collection and processing facilities, and identifying GHG emissions reduction opportunities associated with material-efficient road planning and material recycling all of which will improve waste management and raw material sourcing.[19] With this spatial knowledge, transportation distance of secondary materials from worksites to plants can be accurately estimated, which can help determine the environmental performance and economic feasibility of increasing material circularity in road construction.[20,21]

Belgium covers an area of 30,688 km^2 and hosts about 11.5 million people as of 2020.[22,23] Belgium has one of the densest road networks in the world.[24] In addition, Belgium submitted its first Voluntary National Review to the United Nations in 2017, aiming to implement the United Nations 2030 Sustainable Development Goals.[25] Almost at the same time, the federal and regional governments of Belgium announced a range of measures to boost the transition from a linear economy to a circular economy.[26−29] Belgium's dense road networks, ambitions to promote circular economy, and lack of consistent nationwide frameworks for implementing circular economy practices in the road sector make it an ideal testbed to investigate material stocked in road infrastructure and explore policy implications for material-efficient spatial planning and urban mining.

Against this background, we developed a hybrid bottom-up approach, combining machine learning models and archetypes to map nonmetallic minerals (e.g., asphalt, aggregates, and concrete) stocked in road infrastructure across Belgium. Importantly, to improve layer thickness prediction, we developed a machine learning (ML)-enabled layer-by-layer method by harnessing data on motorways in Flanders (the Dutch-speaking northern portion of Belgium), where adequate data on layer thickness are available for training, validating, and testing ML models. With our ML-enabled layer-by-layer method, we were able to predict the pavement thickness by location for roads whose thickness is unknown, thus improving the accuracy of stock estimation compared to the archetype-based approach. For road categories whose data are inadequate for model training, validation, and testing, we employed a design-guided archetype-based method to predict layer thickness. Our hybrid approach has the potential to significantly advance our understanding of materials stocked in road infrastructure across locations. With the amassed data and high-resolution maps, we explored the patterns of material stock efficiency at multiple scales, the recyclability of EoL road materials across space and by road layer, and the GHG emissions reduction by material stock efficiency improvement and material recycling, aiming to address the following questions.

- Can the ML-enabled layer-by-layer method reveal the spatial heterogeneity in pavement thickness?
- What are the quantities and locations of nonmetallic minerals stocked in Belgium's road infrastructure?
- How does material stock efficiency correlate with population density at multiple scales?
- What are the quantities and locations of recyclable materials in the next decades?
- To what extent can material stock efficiency improvement and material recycling reduce the GHG emissions associated with road construction?
- What are the policy implications for material-efficient spatial planning and urban mining?

2. MATERIALS AND METHODS

2.1. Analytical Scope. The scope of this study covers the Belgian road networks as of 2021, which are governed by three regional governments from north to south: the Flemish Region, the Brussels-Capital Region, and the Walloon Region. The Belgian road networks can be further categorized into four types: motorways, national roads, local roads, and cycleways. Since we focus on the road network per se, bridges (except for the deck part), tunnels (except for the paving), sidewalks, bus platforms, crash barriers, road signs, and lighting systems are excluded. Infrastructures underneath road networks, such as water supply networks, drainage systems, and cables, are out of the scope of this study. Future studies should place particular emphasis on the stocks and associated GHG emissions of concrete and metals used in the excluded subsystems.

We considered three pavement types: asphalt pavement, concrete pavement, and composite pavement. Asphalt pavement is the dominant type compared to the other two. For context, in Europe, more than 90% of roads are paved with asphalt,[30] and this number reaches 94% in the U.S.[31] We considered three materials in this study: asphalt, aggregates (sand, gravel, and stone, which are usually used for the base layer), and concrete. Soils, which are in Belgium usually used for road foundation, are not considered. The reasons for doing so are twofold. First, asphalt and aggregates are the main ingredients in pavement.[32,33] Second, asphalt and aggregates can be reutilized in

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Table 1. Overview of Road Networks Covered by the Resource Cadaster[a]

category	Belgian road networks		asphalt pavement			concrete/composite pavement			sum (%)
	number of segments	length (km)	number of segments	length (km)	percentage of the total length	number of segments	length (km)	percentage of the total length	
motorway	4071	4055	3658	3419	84.3	390	614	15.1	99.4
motorway ramp	4128	660	4057	648	98.2	65	11	1.7	99.9
national road	79,821	12,311	73,211	11,439	92.9	5035	555	4.5	97.4
local road	906,059	113,873	588,186	73,681	64.7	86,358	12,512	11.0	75.7
cycleway	60,952	38,167	24,675	15,956	41.8	10,866	6877	18.0	59.8
path	390,552	54,097							
unknown	278,810	35,468							
sum	17,124,393	258,631	693,787	105,143	40.7	102,714	20,569	8.0	48.7

[a]Note: paths and unknown roads are not considered in material stock mapping.

pavement construction to reduce primary material consumption and environmental burdens.[34,35]

2.2. Data Collection and Preparation. We collected three types of datasets. First, GIS datasets of the Belgian road networks were obtained, providing essential information on the location and topology of different roads. Second, design-related data were gathered to facilitate the training of ML models. Third, population data and the locations of asphalt plants were utilized for analyzing material stock efficiency and estimating the potential for asphalt recycling, respectively. To streamline data management and enable further analysis, the GIS datasets were merged into a unified dataset representing the Belgian road network. The design-related data were incorporated into this merged dataset as additional attributes.

2.2.1. Basic Attributes. To determine the quantities of materials stocked in Belgian road networks, we developed a resource cadaster based on the following GIS datasets.

- The spatial database of registered roads in the Flemish Region and the Brussels-Capital Region.[36] This open-access database updates frequently, and we used the version accessed on 18/03/2021. A new version would achieve similar results because every update only adds a few newly registered roads. This official government database documents over 1 million road segments with detailed attributes, including road category, road number, road width, road manager, and status.
- The spatial database of road networks in the Walloon Region. This database was retrieved from Service public de Wallonie (SPW),[37] which is an official spatial database that documents the road category, road number, and road manager of more than 336,000 road segments.
- The GIS database of cycleways in the Flemish Region.[38] This database records about 19,000 cycleway segments without detailed attributes.
- The GIS database of cycleways in the Brussels-Capital Region.[39] This database inventories 146 attributes of cycleways.
- The GIS database of cycleways in the Walloon Region.[40] This database documents about 8000 attributes of cycleways.
- The GIS database of the Belgian road network from the OpenStreetMap.[41]

These official datasets and crowdsourced geospatial datasets were harmonized into a single dataset, covering the road networks in the entire Belgium.[36−40] When processing the data, we found out that data completeness varies across databases. For example, the Flemish Region documents the road width, whereas the Walloon Region ignores this valuable attribute. We also found that all cycleway networks only have topology information. Besides, we found sporadic overlaps between regional maps. To avoid losing valuable information (e.g., road width), we chose to keep roads documented in Flemish databases that come with detailed attributes. Because not all necessary data are available from official data, we also incorporated a crowdsourced spatial database, i.e., OpenStreetMap,[41] to complement official data (see Section S1.1 in the SI for more details). The difference between official data and crowdsourced data is that the former has the most comprehensive information about motorways, national roads, and local roads (see Section S1.2 in the SI for more details), while the latter has detailed spatial information about other types of roads, such as paths, footways, service roads, and so forth.

2.2.2. Design-Related Data. On top of basic attributes, our resource cadaster also includes the following geospatial datasets that are relevant for pavement design.

- Historical climate data at 1 km spatial resolution.[42] This public dataset includes the global monthly climate data from 1970 to 2000 for minimum, mean, and maximum temperatures, precipitation, and wind speed.
- European soil database.[43,44] This spatial database developed by the Joint Research Center (JRC) is an open-access and high-resolution (1 km) database. A number of layers for soil properties were integrated into our database, including bulk density, clay content, silt content, and sand content.
- Surface information of all roads in Belgium.[45] This dataset was retrieved from HOTOSM, as official datasets do not include surface info.
- The traffic flow (annual average daily traffic, AADT) and pavement structure of Flemish motorways in 2018 were retrieved from AWV, short for the Flemish Agency for Roads and Traffic of Belgium.[46]
- UN Traffic Census 2005,[47] which includes the traffic flow and road width of Belgian motorways in 2005.

Due to the limited coverage of datasets retrieved from AWV, we collected traffic data for Walloon motorways and Flemish motorways from the UN Traffic Census 2005. We assumed that the AADT of the abovementioned motorways increased by 1% annually between 2005 and 2018 based on the estimation of the Conference of European Directors of Roads (CEDR).[48] The structure data of Flemish motorways and the traffic flow data of Belgian motorways were integrated into our resource cadaster based on road numbers and directions. In addition, for the width

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Table 2. Overview of Data Sources by the Road Category

category	length	width	structure	surface	traffic	climate and Soil
Flemish & Brussels motorways	Informatie Vlaanderen,[36] OSM[41]	Informatie Vlaanderen,[36] OSM[41]	AWV[46]	AWV[46]	AWV[46]	WorldClim,[42] JRC[43,44]
Walloon motorways	SPW,[37] OSM[41]	SPW,[37] OSM[41]		HOTOSM[45]	UN traffic census[47]	WorldClim,[42] JRC[43,44]
Flemish & Brussels motorway ramps & national roads	Informatie Vlaanderen,[36] OSM[41]	Informatie Vlaanderen,[36] OSM[41]		HOTOSM[45]		WorldClim,[42] JRC[43,44]
Walloon motorway ramps & national roads	SPW,[37] OSM[41]	SPW,[37] OSM[41]		HOTOSM[45]		WorldClim,[42] JRC[43,44]
Flemish & Brussels local roads	Informatie Vlaanderen,[36] OSM[41]	Informatie Vlaanderen,[36] OSM[41]		HOTOSM[45]		WorldClim,[42] JRC[43,44]
Walloon local roads	SPW,[37] OSM[41]	SPW,[37] OSM[41]		HOTOSM[45]		WorldClim,[42] JRC[43,44]
Flemish cycleways	Toerisme Vlaanderen,[38] OSM[41]	Toerisme Vlaanderen,[38] OSM[41]		HOTOSM[45]		WorldClim,[42] JRC[43,44]
Brussels cycleways	BruGIS,[39] OSM[41]	BruGIS,[39] OSM[41]		HOTOSM[45]		WorldClim,[42] JRC[43,44]
Walloon cycleways	SPW,[40] OSM[41]	SPW,[40] OSM[41]		HOTOSM[45]		WorldClim,[42] JRC[43,44]

of Walloon motorways, we adopted the average width of roads from the UN Traffic Census 2005.

Because official data tend to be more reliable than crowdsourced data, we carefully vetted data merged into our resource cadaster based on official data. First, we corrected the surface type of roads, for which official data are available from AWV. Second, we adjusted the road category of several segments which are misrecorded in the OpenStreetMap. For example, several road segments between motorways are recorded as local roads. We changed their road category to motorways. Table 1 gives an overview of road networks covered in our resource cadaster. As demonstrated in Table 1, we only considered materials stocked in surfaced roads (excluding paths and unknown roads), which have explicit info about their surface type. Table 2 summarizes the data sources by road category. The variability in road thickness can be found in Section S3.1 of the SI.

2.2.3. Other Auxiliary Data. Data for material density and binder content (Table S4) were used to determine the mass of material stocks. We collected the following two datasets, with the former used for analyzing material stock efficiency and the latter for material recyclability.

- Number of residents in Belgium for the year 2018 retrieved from JRC.[49]
- Location and production capacity of 38 asphalt plants in Belgium.[50]

2.3. Hybrid Bottom-Up Stock Mapping. *2.3.1. Overview.* We introduced a hybrid bottom-up approach to map materials stocked in the Belgian road networks (Figure 1a). We quantified the mass of asphalt, aggregate, and concrete stocked in each road segment based on road length, road width, pavement structure, and layer thickness, as expressed in the equations below.

$$MS_{as,i} = \sum_j L_i \times W_i \times T_{i,j} \times \rho_{i,j} \quad (1)$$

$$MS_{b,i} = \sum_j L_i \times W_i \times T_{i,j} \times \rho_{i,j} \times BC_{i,j} \quad (2)$$

$$MS_{c,i} = \sum_j L_i \times W_i \times T_{i,j} \times \rho_{i,j} \quad (3)$$

$$MS_{t,i} = \sum_j L_i \times W_i \times T_{i,j} \times \rho_{i,j} \quad (4)$$

$$MS_{agg,i} = MS_{t,i} - MA_{as,i} - MS_{c,i} \quad (5)$$

where $MS_{as,i}$ is the mass of asphalt stocked in road segment i, L_i is the length of road segment i, W_i is the road width, $T_{i,j}$ is the thickness of layer j, $\rho_{i,j}$ is the density of materials used in layer j, $BC_{i,j}$ is the binder content of layer j, $MS_{b,i}$ stands for the mass of bitumen in road segment i, $MS_{c,i}$ stands for the mass of concrete road segment i, $MS_{t,i}$ stands for the total mass of materials in road segment i, and $MS_{agg,i}$ stands for the mass of aggregate road segment i.

Ideally, location-specific parameters should be used to determine the mass of materials stocked in each road segment. However, owing to the paucity of location-specific data, we employed two methods to predict layer thickness. First, an ML-enabled method was employed to capture the complex relationships between layer thickness and traffic, climatic, and soil conditions for asphalt motorways (Figure 1b). The resulting models were used to predict the layer thickness of asphalt motorways (1995 km by length) where locational information on layer thickness is not available (Section 2.3.2). Second, for all other roads (e.g., concrete and composite motorways, motorway ramps, national roads, local roads, and cycleways, totaling 121,854 km by length), the layer thickness and pavement structure were determined by a design-guided archetype-based method (Section 2.3.3). Archetypes were adapted from AWV (Figure 1c). With geospatially resolved maps of material stocks, we then explored the patterns of material stock efficiency at multiple levels (Figure 1d) and examined material recyclability in the coming decades (Figure 1e).

2.3.2. Machine Learning-Enabled Method. We employed Gradient Boosting Decision Tree (GBDT) to predict the thickness of the base layer and asphalt layer of asphalt motorways. GBDT is a powerful supervised ML technique that can be used in various practical tasks, such as prediction. The CatBoost library was selected because it is a well-established GBDT library and has been widely used by both researchers and practitioners.[51,52]

We developed theory-driven ML models by considering the engineering knowledge from the Mechanistic-Empirical Pavement Design Guide (MEPDG).[53] Inspired by MEPDG, several key factors affecting the pavement design are considered (Figure

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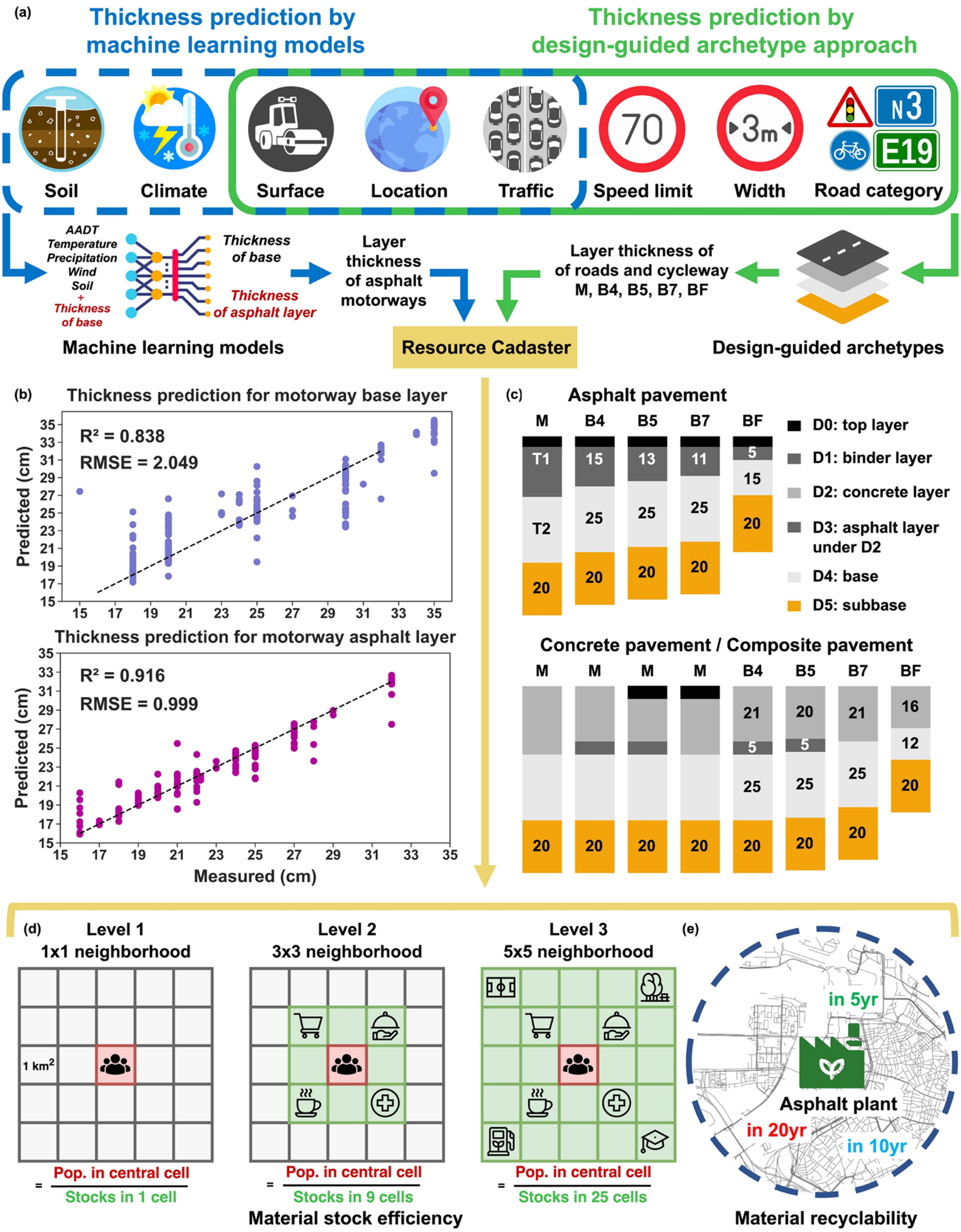

Figure 1. Methodology for mapping material stocks and analyzing material stock efficiency and material recyclability. (a) Hybrid approach for estimating material stocks of Belgian road networks. (b) Predictive performance of ML models used for asphalt motorways. (c) Archetypes used for roads other than asphalt motorways. (d) Definition of material stock efficiency by the commuting distance. (e) Definition of material recyclability. M stands for motorway; B4, B5, B7, and BF stand for construction classes.

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Environ. Sci. Technol. 2023, 57, 12674−12688

1a), including traffic flow (AADT), monthly average temperature, monthly average precipitation, monthly average wind speed, and soil conditions (i.e., soil density, moisture, clay content, silt content, sand content, and coarse fragments). Besides, we developed ML models in a layer-by-layer fashion; in other words, the thickness of the base has an impact on the thickness of the asphalt layer (Figure 1a), which to a great extent reflects the common practice in road design (see Section S2.1 in the SI for more details).

Thanks to AWV's continuous effort in collecting location-specific data, we were able to train CatBoost models with a dataset that covers 990 motorway segments in Flanders. All segments in this dataset include information on AADT and road structure.[46] Before training, we removed 36 segments that were identified as outliers (base < 10 cm or > 40 cm, asphalt layer < 15 cm) and kept 954 segments (1249 km, 32% of the total motorway network) for model training, validation, and testing. We used the Optuna library[54] to find the optimal combination of hyperparameters (i.e., learning rate, l2 leaf reg, and max depth). A 5-fold cross-validation and Bayesian optimization were used when optimizing hyperparameters. Cross-validation is a widely employed technique in applied machine learning to assess the predictive performance of a model on unseen data. In essence, the objective of cross-validation is to estimate a model's performance in real-world scenarios where it encounters new, unseen data. By assessing the model's predictive ability on data that are not included in the training process, cross-validation enables us to gauge its generalization capabilities. In assessing the accuracy of the trained model, we employed R^2 values, which represent the squared correlation between the test data and the predicted values by the trained model. Once the model training was complete, we predicted the thickness of target motorways: 2495 motorway segments (total length is 1995 km, with 2117 segments in Wallonia and 378 segments in Flanders) with AADT information but without structure information. As shown in Figure 1b, the trained models allowed us to predict the thickness of the base (T2) and the asphalt layers, including a 4 cm top layer (D0) and a binder layer (T1). Specifically, the models lead to R^2 values in excess of 0.8 (0.838 for the base and 0.916 for the asphalt layer), indicating that the layer-by-layer method performs well in predicting the pavement thickness for motorways. In addition, the mean root-mean-square error (RMSE) is 1.0 cm for the asphalt layer and 2.0 cm for the base. The variability in layer thicknesses of Belgian road networks and motorways can be found in Figure S3. There were still 172 motorway segments without AADT information; for these segments, we assigned the average thickness of the asphalt layers (22.7 cm) and bases (24.2 cm) of motorways with AADT information.

2.3.3. Archetype-Based Method. Pavement design usually takes into account road class, road surface, location of the road (inside/outside built-up areas), speed limit, lane width, and AADT (Figure 1a). Flanders has 11 construction classes (or road archetypes).[55,56] First, we determined the archetype per road category via an online platform of pavement design developed by AWV.[55] With this platform, we assigned an archetype to each road category based on the preceding influencing factors. The detail of the archetype assigning is available in the Supporting Information (SI). Due to the inconsistencies in the way how roads are categorized in various databases and across regions, we had to make several assumptions when assigning an archetype to a road category (see Section S1.4 in the SI for more details). For consistency across regions, we did not differentiate between primary and secondary roads. For the Walloon concrete motorways, we used the average layer thickness of Flemish concrete motorways. For primary roads (under the category of national roads) in Flanders, we used the archetype B4. For secondary roads (also under the category of national roads) in Flanders, we used the average of archetypes B4 and B5. For motorway ramps in the entire Belgium and Walloon national roads, we assumed that their thickness is equal to the average of archetypes B4 and B5. For local roads and cycleways in the entire Belgium, we used the archetypes B7 and BF, respectively. For asphalt pavements in the entire Belgium, a cement-stabilized crushed stone foundation is considered the base since it is broadly applied in Belgium.[57,58] For composite and concrete pavements in the entire Belgium, lean concrete has been frequently used as the base.[58] We therefore assumed that the subbase is made of crushed stone with a minimum thickness of 20 cm.[56]

2.4. Measuring Material Stock Efficiency.

Material efficiency measures aim to decouple resource use from service provision. While there are a variety of indicators to measure material efficiency,[59] we herein focus on material stock efficiency, i.e., service provision divided by material stock, to measure the material stock efficiency of the Belgian road infrastructure, as it represents the capacity of the road infrastructure to deliver mobility services.[60]

Materials stocked in road networks provide mobility services to the population within and across neighborhoods. Ideally, mobility service-related indicators (e.g., person-km, tonne-km, number of trips, travel time, etc.) should be used for gauging the material stock efficiency of road infrastructure as in the study of Virág et al.,[61] but spatially refined data on mobility services are not available. Therefore, we defined material stock efficiency as the number of the population served per unit mass of material stock. Due to the format of population datasets, we rasterized them in our resource cadaster. As there is no established definition for measuring road infrastructure's material stock efficiency at a spatially refined level, we measured the material stock efficiency of the Belgian road infrastructure at three spatial levels (Figure 1d).

- At level 1, material stock efficiency is determined by the population living in a 1 km^2 cell (a proxy for a neighborhood) divided by the mass of material stock within this neighborhood; within a 1 km^2 neighborhood, people have access to public transport and grocery stores.
- At level 2, material stock efficiency is determined by the population living in the 1 km^2 central cell divided by the mass of material stock within a 9 km^2 neighborhood; within a 9 km^2 neighborhood, people have access to supermarkets, restaurants, cafes, pharmacies, etc.
- At level 3, material stock efficiency is determined by the population living in the 1 km^2 central cell divided by the mass of material stock within a 25 km^2 neighborhood; within a 25 km^2 neighborhood, people have access to most daily facilities and jobs, including workplaces, sports fields, parks, schools, filling stations, and so forth.

In addition to measuring material stock efficiency at three levels, we also investigated the patterns of material stock efficiency in urban areas of large cities. We defined urban areas as the cells that are intersected or within a 5 km radius of the city center.

2.5. Modeling Material Recycling Potentials.

The transport distance between EoL road materials and material

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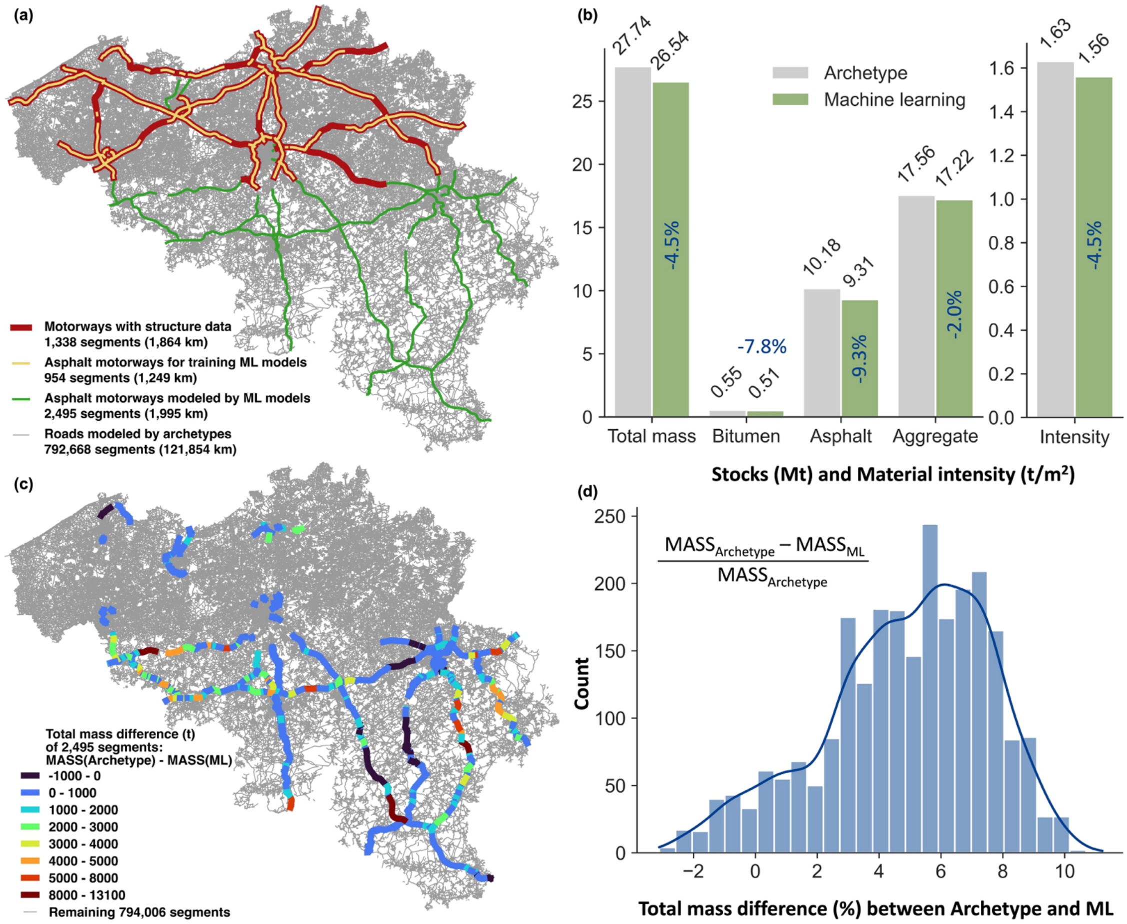

Figure 2. Comparisons between the ML-enabled method and the archetype-based method. (a) Roads modeled by ML models and archetypes. (b) Comparison of material stocks and material intensity. (c) Comparison of total mass difference across 2495 segments. (d) Distribution of total mass differences.

processing facilities (e.g., asphalt mixing plants) is one of the key factors that determine the viability of recycling EoL road materials.[21] We limited this analysis to recycling of asphalt materials from Belgian road networks at their EoL due to the lack of data on locations of processing facilities for other materials. We used 20 km as an indicative threshold to determine the viability of recycling EoL asphalt, as it is environmentally beneficial to recycle materials that are at most 20 km from material processing facilities.[21] In doing so, we used the location and capacity of 38 asphalt mixing plants in Belgium. Furthermore, we analyzed the recyclability of materials stocked in Flemish motorways in the coming decades, as only these roads have info on their year of commissioning. Should more data become available, similar analyses can be done for other roads.

2.6. Estimating GHG Savings from Improving Material Stock Efficiency and Recycling. To estimate GHG emissions saved by material stock efficiency improvement, we designed three counterfactual scenarios for the top 20 most populous cities: (1) high, (2) national average, and (3) low. We modeled a hypothetical increase/decrease of urban density, which would decrease/increase the need for road stocks. In the counterfactual “high” scenario, we assumed that roads in the top most populous 20 cities were constructed in a way that they deliver a high level of material stock efficiency on par with the most material-efficient city, Namur (69 pop/kt). In the “national average” scenario, we assumed that roads in the top 20 most populous cities were constructed to deliver a level of material stock efficiency (22.4 pop/kt) on par with the national average (including both urban and rural areas). For the “low” scenario, we assumed that roads in the top 20 most populous cities were constructed to deliver a lower level of material stock efficiency (15.6 pop/kt) on par with the least material-efficient city. Though the “low” scenario would not be applied in developed countries (e.g., Belgium), we decided to keep it as it will deliver insights into improving material stock efficiency for developing and underdeveloped countries. The material stock of a 1 km^2 cell was calculated using the population living in this cell divided by the above stock efficiencies. We then calculated the total stocks by summing up stocks by cell and estimated the GHG emissions associated with material savings using Belgium-specific GHG emissions factors (Table S7).

To estimate GHG emissions saved by material recycling, we compared the GHG emissions from reusing reclaimed asphalt pavement (RAP) and using virgin materials in pavement reconstruction. As most RAP in Flanders is recycled in central asphalt mixing plants,[20] we included GHG emissions from road deconstruction, transportation of RAP to plant or storage site, material phase, asphalt production, transportation from plant to worksite, and construction (Table S8). It should be noted that we did not consider future changes in GHG emissions per unit of virgin materials and reused RAP.

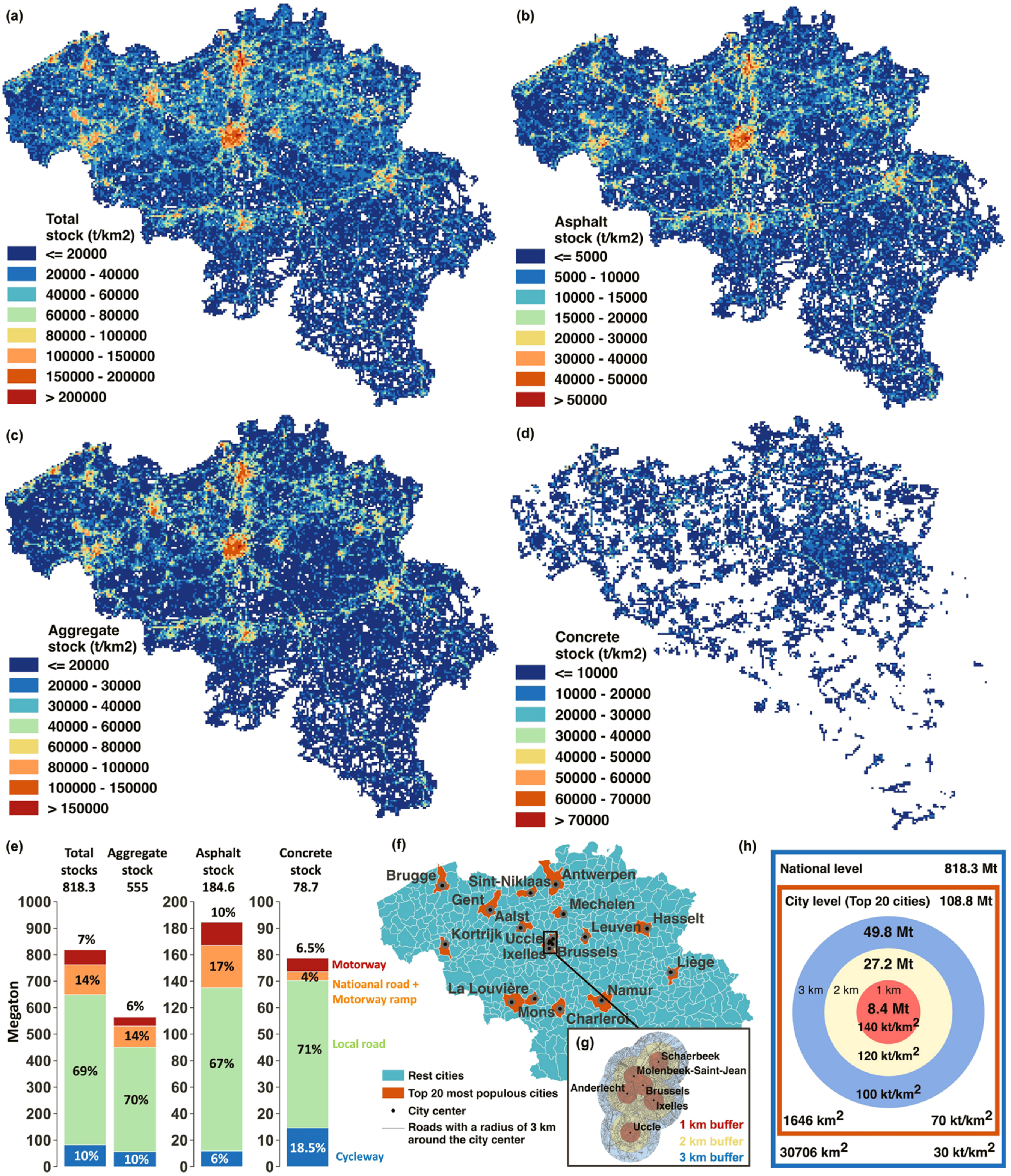

Figure 3. Spatial distribution of materials stocked in the Belgian road networks. (a) Spatial distribution of total material stocks. (b) Spatial distribution of asphalt stocks. (c) Spatial distribution of aggregate stocks (without aggregates in asphalt). (d) Spatial distribution of concrete stocks. (e) Material stocks by the road type. (f) Top 20 most populous cities. (g) Zoom-in view of material stocks within different radii around the city center. (h) Total material stocks within highly urbanized areas. Note: we treated motorway ramps as national roads because the former's archetype is the same as the latter's.

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Environ. Sci. Technol. 2023, 57, 12674−12688

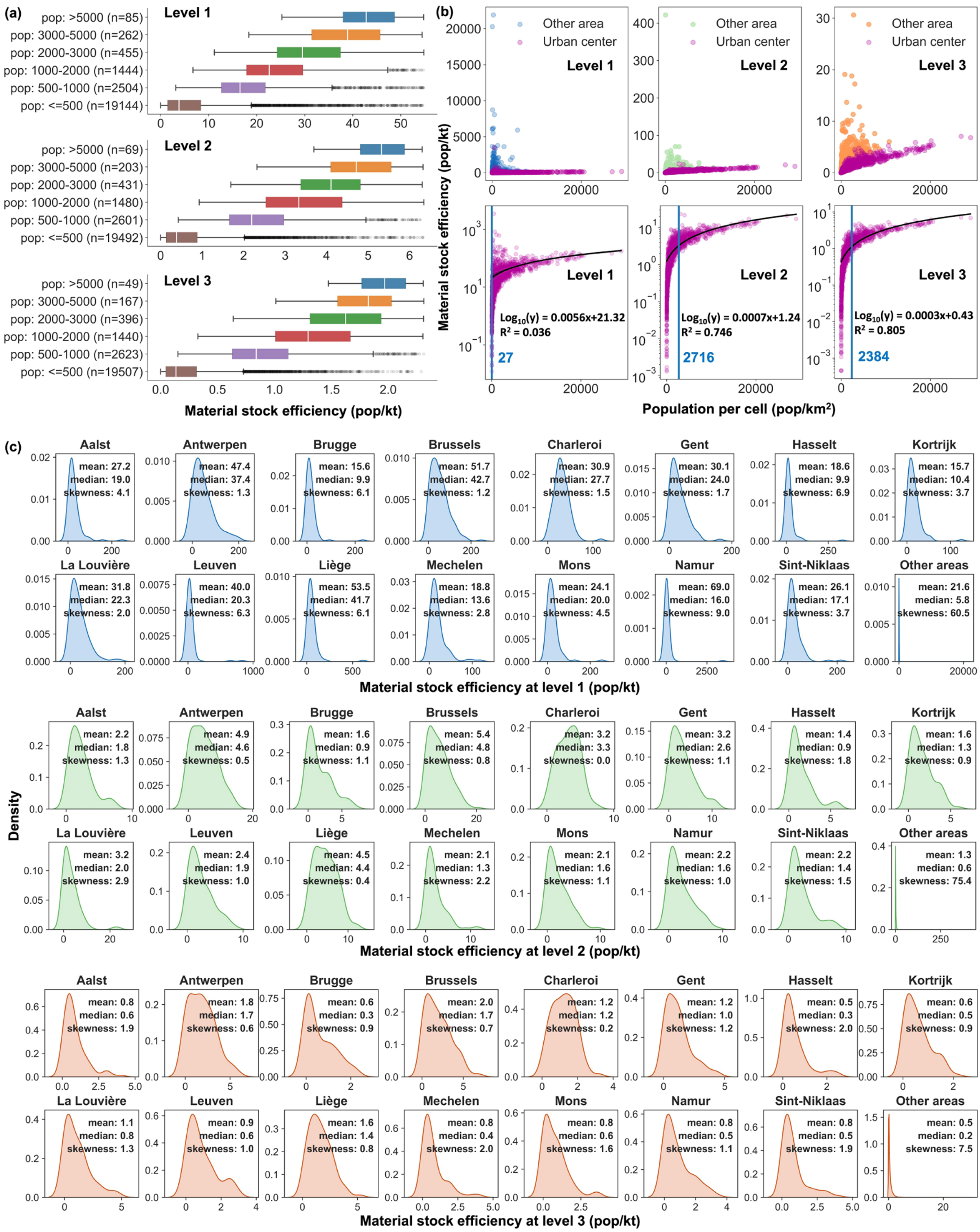

Figure 4. Material stock efficiency across space and cities. (a) Box plots of material efficiency at different levels with whiskers extending to ±3 interquartile ranges at different levels. (b) Relationship between material stock efficiency and population density. Note: the blue lines signify that material stock efficiency gains by increasing population density have reached an inflection point, which is estimated by a Python function named numpy.diff.argmax.[65,66] (c) Statistical distribution of material stock efficiency at different levels and across cities.

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Environ. Sci. Technol. 2023, 57, 12674−12688

3. RESULTS

3.1. Performance of the Machine Learning-Enabled Method. Figure 2a gives an overview of which roads are modeled by the ML-enabled method and which are modeled by the archetype-based method. In this study, we harnessed a dataset of 954 Flemish motorway segments to predict the pavement thickness of 2495 motorway segments. For the roads modeled by the ML-enabled method, we performed additional analysis using an archetype selected from the 954 motorway segments that have structure information. As indicated by the comparison between the results of the ML-enabled method and the additional analysis using the archetype-based method (Figure 2b−d), the ML-enabled method can generate results comparable to the archetype-based method (Figure 2b) and reveal the variability in layer thickness across locations (Figure 2c,d). This nuanced understanding can help improve stock estimation across space, facilitate waste managers in efficiently allocating their logistics, and enable accurate estimation of transportation-related environmental impacts.

As mentioned earlier, most existing studies employed an archetype-based method that cannot reflect locational heterogeneities in road properties governed by traffic, climatic, and soil conditions. Our method advances material stock mapping in two ways. First, the results demonstrated the feasibility of leveraging ML models to capture the complex relationships between the layer thickness and traffic, climatic, and soil conditions. Second, since locational thickness data are not always available, our method opens the possibility of using limited data to help determine the pavement thickness across locations, a crucial geometric attribute in material stock estimation.

3.2. Spatial Distribution of Materials Stocked in Belgian Road Networks. Results show that the spatial distribution of materials stocked in Belgian road networks is characterized by a similar pattern across total stocks, asphalt stocks, and aggregate stocks (Figure 3a−c). Metropolitan areas (densely populous areas) and motorways are the places where the accumulation of these materials occurs. However, this pattern is not apparent for concrete stocks (Figure 3d) because concrete is less commonly used in urban areas due to its relatively higher price, concerns about concrete pavement-induced noises, long construction and rehabilitation time, and complex road configuration. Moreover, material stocks are more concentrated in metropolitan areas in Flanders compared to those in Wallonia because 95% of the Flemish population lives in urban areas, thanks to Flanders' urban planning policies.[62]

As of 2021, the mass of materials stocked in Belgian road networks amounts to 818.3 Mt, including 555 Mt of aggregate, 184.6 Mt of asphalt (of which bitumen accounts for 9.6 Mt, see details in Section S3.2 of the SI), and 78.7 Mt of concrete (Figure 3e). Our estimates are consistent with previous estimates[63] using archetypes (Figure S5). One counterintuitive fact observable from Figure 3e is that local roads are the main reservoir of materials, which coincides with the finding from a previous study.[8] This is because local roads are the most common road in Belgium, making up 69% of the total road length. Even though motorways and national roads merely account for 3 and 10% of the total road length, respectively, they account for 21% of the total material stock, which is attributable to their wider surface and thicker layers. Cycleways make up 18% of the road networks by length, and their slim and thin structure leads to a relatively small stock of materials (10%). Interestingly, an increased share of motorways and national roads can be observed in asphalt stocks because most motorways (84% by length) and national roads (93% by length) are paved with asphalt.

When limiting the scope to urban areas (Figure 3f−h), we find that the mass of material stocks per area (except for concrete) is higher in large cities. The top 20 most populous cities, home to a population of 2.8 million, accommodate 24.5% of the entire Belgian population. Materials accumulated in the top 20 most populous cities represent 13.3% of the material stocks in Belgian road networks (818.3 Mt), whereas they only occupy 5% (1646 km^2) of the Belgian territory (Figure 3h). Moreover, the top 20 most populous cities have accumulated 49.8 Mt of materials within a 3 km radius of the city center, accounting for about 47% of total material stocks (108.8 Mt) within the municipality boundary (Figure 3h). Perhaps unsurprisingly, the density of material stocks decreases with distance from the city center (Figure 3h). The density of material stocks within a 1 km radius of the city center is 140 kt/km^2, which is twice the average city level (70 kt/km^2) and almost quintuple the density at the national level (30 kt/km^2). To put these results into perspective, the national average densities of material stocks of road infrastructure in Austria, Germany, Norway (including motorways, national roads, and local roads), and the United States (unsurfaced and unpaved roads are also included) are 18,[14] 24,[14] 11,[15] and 1.5 kt/km^2,[5] respectively; the calculation of these values can be found in the SI. These observations reflect that materials tend to accumulate in urban areas, which serve as hubs for residential spaces, job opportunities, entertainment, and commercial activities. As such, special attention should be paid to road networks in urban areas to ensure good pavement performance. In the context of circular economy, urban road networks will play a dominating role in material recycling because the material stocks are more accumulated in urban areas where less transportation effort is needed than in rural areas.

3.3. Patterns in the Relationship between Material Stock Efficiency and Population Density. With high-resolution maps of material stocks and population density, we were able to measure the material stock efficiency at three levels, as defined in Section 2.4. The resulting maps (Figure S5) and box plots show that neighborhoods with higher material stock efficiency tend to concentrate around densely populated hubs (Figure 4a). In addition, if the spatial units are grouped by population density, we found significant cross-group heterogeneity in average material stock efficiency at each level but with less heterogeneity at level 3, as services provided by material stocks at level 3 are more broadly shared by surrounding residents.

City-level results conform to a similar pattern. As shown in Figure 4c, the top 20 most populous cities universally exhibit a strongly right-skewed distribution across three levels, indicating that a few neighborhoods utilize their road infrastructure more efficiently. The ubiquity of right skewness may be explained by the highly hierarchical structure of Belgian cities. Historically, Belgium's centuries-old cities have been surrounded by farmland, with the wealthier residing in the city center and the poorer living in the city's outskirts. Although this pattern has been to some extent changed by the advent of decentralization technologies (e.g., automobiles and railways) and the expansion-oriented urban planning policies taking place in Flanders in the past,[64] the spatial structure of contemporary road networks largely follows their historical pattern. As such, compact areas where populations are concentrated are associated with more

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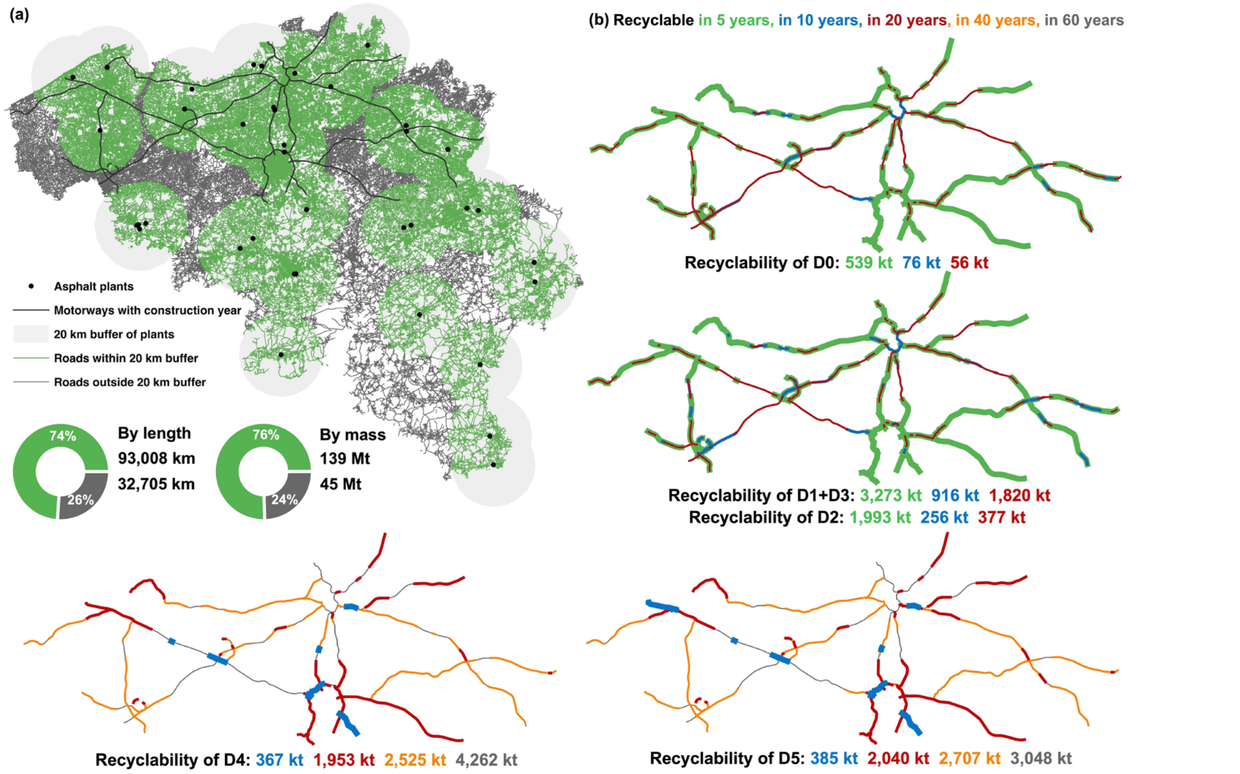

Figure 5. Material recycling potentials across space and by road layer. (a) Asphalt recycling potentials based on the proximity of asphalt mixing plants. (b) Material recycling potentials of Flemish motorways by road layer.

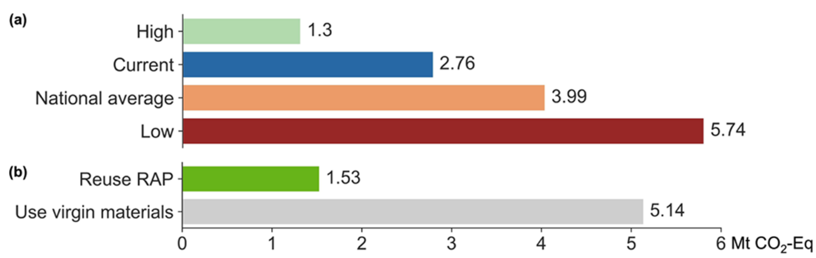

Figure 6. GHG savings by material stock efficiency improvement and material recycling. (a) GHG emissions associated with roads constructed in the top 20 cities in various levels of material stock efficiency. (b) GHG emissions from reusing reclaimed asphalt pavement (RAP) and using virgin materials in pavement reconstruction.

efficient use of road infrastructure and, therefore, higher material stock efficiency.

To test how material stock efficiency correlates with population density, we contrasted material stock efficiency with population density within urban and rural areas (Figure 4b). As expected, material stock efficiency positively correlates with population density in urban areas, but there is no clear correlation between material stock efficiency and population density in rural areas. The most intriguing feature of the results is perhaps that stock efficiency increases with population density, but material stock efficiency gain starts diminishing when population density reaches around 2500 pop/km^2. This feature becomes most apparent in levels 2 and 3, which strongly suggests that there is a universal nonlinearity at play that underlies the correlation between material stock efficiency and population density.

3.4. Spatial Distribution of Recycling Potentials for Asphalt.

As defined in Section 2.5, recyclability of EoL asphalt materials is determined by the proximity of road segments to asphalt mixing plants, where EoL asphalt materials can be circulated back to new products. Figure 5a shows that 76% (139 Mt) of the asphalt materials stocked in Belgian road networks are already potentially recyclable as their accumulation occurs at places in close proximity to asphalt mixing plants. In addition, realization of these material recycling potentials requires a detailed evaluation of the performance of each pavement layer, which can help determine the best timing to recycle multiple layers concurrently. Perhaps equally importantly, material recycling must take into account maintenance scheduling of other infrastructure systems (e.g., pipelines and cables) alongside or underneath road infrastructure to avoid ill-planned maintenance work.

The proximity of road segments to asphalt mixing plants does shed light on the likelihood of recycling EoL asphalt materials when they become available. However, understanding the readiness to do so requires a more in-depth analysis of when EoL asphalt materials will become available. The readiness to recycle EoL asphalt materials stocked in Flemish motorways was evaluated because we were only able to determine the year of commissioning for these roads due to data availability. Although

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Environ. Sci. Technol. 2023, 57, 12674−12688

the actual lifetime of asphalt pavements is determined by various influencing factors (e.g., climate, traffic), we assumed that the lifetime of asphalt and concrete layer is 20 years and the lifetime of base and subbase is 60 years based on the guideline released by Flemish transportation authorities and previous studies.[8,56] Therefore, the readiness to recycle EoL materials stocked in a road segment is represented by the difference between lifetime (20 or 60 years) and road age. As shown in Figure 5b, 539 kt (80.3%) from the top layer (D0), 3273 kt (54.5%) from the asphalt layers (D1 + D3), 1993 kt (75.9%) from the concrete layer (D2) can become recyclable in 5 years. For asphalt and concrete layers, 9.7−15.2% of materials can become recyclable in 10 years and 8.3−14.4% of materials can become recyclable in 20 years. For base and subbase, 2525 kt (27.7%) and 2707 kt (33.1%) can become recyclable in 40 years and 4262 kt (46.8%) and 3048 kt (37.3%) can become recyclable in 60 years.

3.5. GHG Savings from Improving Stock Efficiency and Asphalt Recycling. As shown in Figure 6a, if the road infrastructure in the top 20 cities were constructed in a more material-efficient way (high scenario), the GHG emissions associated with material production, transportation, and construction would have been reduced by 53%. However, if the road infrastructure in the top 20 most populous cities were constructed in a less material-efficient way (low scenario), the corresponding GHG emissions would have a 108% increase compared to the current level. In addition, if the road infrastructure in the top 20 cities were constructed in a way that is on par with the national average level, the corresponding GHG emissions would have increased by 45%. This finding highlights the GHG benefits of more material-efficient road planning.

Figure 6b shows that if RAP generated over the next 20 years is fully reutilized, the GHG emissions associated with material production, transportation, and construction over the next 20 years could be reduced by 70%. The significant GHG savings are mainly attributable to reduced consumption of raw materials and less freight transportation (see Table S8). One caveat for interpreting the results presented here is that reusing RAP may affect the performance and lifetime of pavements. In addition, the mechanical property of pavements is affected by not only the RAP content and recycling technology but also weather conditions and traffic load.[20] These factors influence the lifetime and maintenance interventions of pavements and should be carefully considered in future studies evaluating the GHG benefits of RAP recycling.

3.6. Discussion and Future Research. We introduced a hybrid approach to maximizing the potential of data pooled from various sources. Since location-specific data are available to train ML models for asphalt motorways, we employed trained ML models to predict the pavement thickness of asphalt motorways in Wallonia, capturing the locational differences in pavement thicknesses due to varying climatic, soil, and traffic conditions. When data are inadequate to reflect the locational differences for other road categories, we adopted an archetype-based method to approximate their pavement thickness. Should data on other road categories become available, the ML-enabled method can help reveal the locational differences for other road categories, improve the accuracy of material stock mapping, and provide a sound foundation for further analysis.

Material stock mapping allowed us to explore the patterns of material stock efficiency at multiple scales, the recycling potentials of EoL road asphalt materials across space and by road layer, and the hypothetical GHG savings by improving stock efficiency via spatial planning and material recycling. However, our analysis was only able to provide a snapshot of materials stocked in road infrastructure due to the complexity of accurately predicting pavement lifetime, which is subject to traffic, climatic, pavement structure, material properties, etc.[67,68] To provide a dynamic analysis of the amount of EoL materials available over the next decades, future research should incorporate design lifetimes and pavement deterioration models into stock-flow modeling to provide robust estimates of future material flows and recycling potentials. Ideally, this then enables modeling the synergies and tradeoffs between changes in spatial planning and in mobility patterns affecting road lifetimes and the effects of improving material recycling.

Our results suggest that compact areas use road infrastructure more efficiently, resulting in higher material stock efficiency. This finding is encouraging for cities wishing to develop material-efficient spatial planning policies and adds additional incentives for recent "No net land take" policies in the EU and Belgium.[69,70] However, the population density of a city cannot increase unlimitedly, which begs the question of under what conditions material stock efficiency gains with increased population density will reach a ceiling. Besides, our results reveal a strong but nonlinear correlation between material stock efficiency and population density. This finding has important implications for cities in developing countries, as their road infrastructure is yet to be built up. Cities in developing countries can shape more compact neighborhoods through a combination of measures, such as implementing appropriate land use policies (e.g., "Stop Concrete" and "Construction Shift" policies in Belgium[71]), pricing congestion, and building public transportation systems.

While a large fraction of the asphalt materials stocked in Belgian road networks is potentially recyclable, there are a few barriers to overcome. In Flanders, over 1.6 Mt of RAP is generated per year,[20] but it is not allowed to use RAP in the top layer due to engineering considerations.[58] The current practice is that 60% of generated RAP (1 Mt) is used in asphalt mixtures for the binder layer and 39% (0.6 Mt) is used as an aggregate for the foundation.[20] Increasing the recyclability of EoL asphalt materials will require new asphalt plants or innovative technologies, such as in situ recycling technologies. Compared to in-plant recycling, in situ recycling reduces material transport and requires only a few additives.[72] Besides, the average distance between worksites and asphalt plants is 43.3 km,[20] and in situ recycling can further shorten the freight transport distance, contributing to GHG emissions mitigation. A recent Italian study also suggests that in situ recycling can save 9% of greenhouse gas emissions compared to in-plant recycling.[73] However, in situ recycling comes with a price, as it requires a longer mixing time and a higher mixing temperature.[72] Due to these drawbacks, in situ recycling is not widely applied in Flanders, and in-plant recycling still plays a predominant role in recycling RAP. Sound decision-making should consider detailed economic and environmental assessments, such as LCA[74] and LCCA,[75] and engagement of relevant stakeholders along the value chain (e.g., road designers, road agencies, waste managers, and urban planners).

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c08703.

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Environ. Sci. Technol. 2023, 57, 12674−12688

Details about data processing, development of the resource cadaster, and additional results, including the thickness of pavement layers, bitumen stocked in Belgian road networks, spatial characteristics of material stock efficiency, comparison with previous studies, and calculations about GHG savings by material efficiency improvement and material recycling (PDF)

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Notes

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