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A bottom-up building stock quantification methodology for construction minerals using Earth Observation. The case of Hanoi

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ABSTRACT

Increasing demand for significant volumes of construction materials, especially sand for use in concrete, in rapidly developing urban environments is becoming a significant socio-economic and environmental issue. The consumption of concrete (comprised of sand, aggregates and cement) is especially concerning on a city level as vast volumes of materials are extracted within the urban hinterland, causing direct impacts locally and the potential for supply issues directly impacting city level metabolism. Excessive consumption and poor management of these materials make it increasingly hard for society to ensure new urban development and infrastructure projects, essential for maintaining the health of cities, meet sustainable development objectives. However, it is difficult to implement suitable resource management policies without first understanding how materials are produced and consumed at an appropriate spatial level. For many areas, especially on a city level, such data is absent, especially so for sand and aggregates which can further exacerbate these local supply issues and environmental impacts. This study attempts to address this data gap via combining earth observation datasets with estimates of materials contained within urban infrastructure (material intensities) to calculate the rapid increase of construction material stocks in Hanoi. Spatial data on buildings have been gathered using, producing, and collating a variety of spaceborne open-source datasets on built up areas (GlobalMLBuildingFootpint, World Settlement Footprint 3D, Open Street Map) and land use classification maps. Linking this spatial data with estimated quantities of sand, gravel, cement and concrete in typical buildings in Hanoi enables quantification of building stocks for a range of building types over a time series. The results show that for every new km^2 of urban infrastructure approximately 520,000 tonnes of concrete, or 360,000 tonnes of sand, 580,000 tonnes of gravel and 115,000 tonnes of cement are required. If the Hanoi Masterplan is to be achieved by 2030, then the material demand is likely to be for 106 million tonnes of concrete or 73 million tonnes of sand, 118 million tonnes of gravel and 24 million tonnes of cement. These all exceed historical consumption trends and are far in excess of current extraction rates and therefore careful planning is required to ensure access to sustainable resources into the future.

1. Introduction

Construction raw materials include a wide range of metallic and non-metallic materials, from steel and aluminium to sand, gravel and clay for bricks which determine a series of environmental impacts linked to their extraction and use. However, it is materials that are extracted in large volumes, from the urban hinterland, that have the greatest effect locally on a city level (Gallagher and Peduzzi, 2019; UNEP, 2017). Materials that are used in bulk (mainly for the manufacture of concrete), are transported short distances, are often extracted within the urban hinterland and have a range of local environmental consequences unlike metals and industrial minerals which are traded internationally. Due to its low cost, high strength and ease of local manufacture concrete is, and will likely remain a fundamental building block of modern cities. Aggregates are also required for fill material, mortar, sub-base, etc., all essential for the construction of buildings, roads, railways and associated infrastructure.

Aggregates are the second largest resource used globally by tonnage (UNEP, 2017) and the extraction of such large amounts of material inevitably leads to local conflict and impacts to often vulnerable

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ecosystems (Dung, 2011). The sheer scale of extraction, especially for sand, and poor management practices leads to erosion, damage to infrastructure, increased flooding risk, habitat loss, pollution, soil degradation and destruction of farmland (Schiappacasse et al., 2019). Supply disruption caused by this unsustainable demand can also cause material shortages, which can lead to illegal mining, rapid price fluctuations and delays to major construction projects, impacting economic growth (Gallagher and Peduzzi, 2019; Torres et al., 2021). Coupled with this, cement (principally consumed in concrete) is a major global emitter of CO_2 (Ellis et al., 2020) and contributor to global warming (Benhelal et al., 2013). The manufacture of cement is accountable for around 8% of global emissions (Ellis et al., 2020), and, as such, its use should be carefully managed.

As aggregates mining is mostly small-scale, informal, and localised in nature there is often little information on where sand is mined, how much is produced or where it is consumed. This lack of understanding and data is a significant global problem highlighted by UNEP (UNEP, 2017). As stated in Vander Velpen et al. (2022), Gallagher and Peduzzi (2019) and UNEP (2017) currently, for many countries, there is little quantitative data available for aggregates and their consumption rates and even less at city level. Also, the sourcing of construction materials is often poorly considered in the urban planning. This study attempts to address this problem with a methodology for a monitoring system for aggregates consumption on a city scale, using freely accessible open source data.

With increasing global pressure for sustainable development, a shift towards a circular economy and the delivery of the Sustainable Development Goals (SDGs) a greater understanding of how materials with high local impact, such as aggregates, flow through our society is required (Vander Velpen et al., 2022). This study highlights the importance of understanding the stocks of construction materials so that that supply risks, as well as environmental issues are identified and urban planning is delivered effectively. This allows for the development of interventions that manage issues such as price volatility, environmental impacts and the lack of transparency of the extractive sector. More information can lead to better decision making, appropriate regulation and a reduction in informal mining practices. In addition, if effective strategies are to be developed for alternatives to virgin materials, such as recycling of building materials from Construction, Demolition and Earthmoving Waste (CDEW), planners require information on the quantities of material that may be available from these sources (Dung, 2011; Gallagher and Peduzzi, 2019; Torres et al., 2021).

These data gaps and lack of publicly available data require new innovative methodologies to assess supply and consumption of construction materials. Where traditional data collation (from mineral extraction or construction sites) may be absent, satellite Earth Observation (EO) data can provide a cost- and time-efficient alternative to data gathering focussing on the materials consumption rather than the production.

Satellite images have the added benefit of providing consistent imagery at global scale and high temporal and spatial resolutions (Bagan and Yamagata, 2014; Lefebvre et al., 2016). Such advancements have increased our capabilities in monitoring and analysing urbanization processes. However, the use of EO and Geographic Information Systems (GIS) data in combination with MFA modelling to uncover the patterns of material stocks and flows in infrastructure development, is still in its infancy (Baynes and Musango, 2018; Haberl et al., 2021; Han et al., 2018; Mao et al., 2020; Peled and Fishman, 2021; Stephan and Athanassiadis, 2018) and requires access to commercial satellite data for analyses at city scales. Recent EO datasets such as night-light satellite images have been successfully used as a proxy for assessing urban development in MFA studies (Han and Xiang, 2013; Takahashi et al., 2010) or to monitor extraction of construction materials in Myanmar and China (Duan et al., 2019; Gruel and Latrubesse, 2021). Additionally, integrating EO data with studies on material flows and stocks has been shown to be an effective technique by Novellino et al. (2021) for filling data gaps, linking material consumption to land use change and forecasting demand trends.

This study integrates EO data with MFA modelling to quantify in space and time urban material stocks as an alternative to previous works (see Section 4.1 for a brief bibliographic review) that rely mainly on large-scale data (from national to regional level) which are often absent or inaccurate for prediction at city-level. The novelty of our work is not in the approach used (see Section 1.1) but in the specific combination, for the first time, of different and complementary EO products.

1.1. Applications of earth observation for quantitative assessment of material stock

Using EO to quantify material stock as top-down approach is not new and so far most of the contributions can be grouped in the following categories.

- Analyses at continental or national scales using open-source EO data such as Sentinel-1 and Sentinel-2 (Haberl et al., 2021). These can be good for understanding patters of socioeconomic indicators such as population, economic activity, and energy consumption but it does not provide sufficient and detailed information for city planning.
- Nightlight radiance, usually from the VIIRS instrument onboard the Suomi National Polar-orbiting Partnership satellite, as a proxy to retrieve built-up volumes (Peled and Fishman, 2021). The issue with this approach is the coarse resolution of the data (>375m) and the inapplicability at local/city-scale.
- Studies based on high-resolution datasets such as volumetric information from LiDAR data or reliant on specific and difficult to reproduce datasets such as historical maps (Guo et al., 2021; Miatto et al., 2019). The main limitation with these methods is the lack of availability and varying quality/details of the inputs. For example, older maps and aerial photographs lack geo-referencing, are often only retrievable in historical prints, and in some cases are hand-drawn. These conditions limit the reproducibility of the method.

With our work, we try to close the gap between coarse material stock estimates covering large areas and highly detailed cadaster-based studies limited to small areas which are lacking, especially in rapidly growing cities. Compared to previous studies and as far as the authors knowledge, we use and compare freely-available high-resolution EO datasets into a building stock analysis for the first time: Global-MLBuildingFootprint (GBF), World Settlement Footprint (WSF) 2019 and Google Open Building (GOB) (see Section 2.2 for more details).

For some cities comprehensive studies have been conducted to quantify a range of building materials, for example Amsterdam, Melbourne, Rio de Janeiro and Tiexi (Condeixa et al., 2017; Guo et al., 2021; Stephan and Athanassiadis, 2018, Van der Hoek et al., 2017; Voskamp et al., 2017). Such analysis relies on a large volume of publicly available data, for example from construction documents, such as Bills of Quantities, for existing and new buildings, detailed spatial data for building types and locations or from detailed government planning documents. For a 'bottom up' approach, where data on stocks and flows of materials are collated from primary sources at site/project level, data needs to be integrated with expert knowledge of local building practices, architecture etc. Although such analysis can produce relatively high levels of confidence in the material flow data produced and are an established methodology for city level Material Flow Analysis (MFA) (Guo et al., 2021; Haberl et al., 2021; Lanau and Liu, 2020; Stephan and Athanassiadis, 2017; Yu et al., 2021), They rely on the presence of existing high-quality data from aerial photos, plans, GIS, LIDAR surveys etc. For many cities such data may not exist, or they will be in many disparate documents, sometimes confidential or privately owned, often compiled for different purposes and according to a range of standards, such as building plans or local planning documents.

1.2. Hanoi case study

Hanoi is an ideal case study for the development of a hybrid EO – MFA modelling approach for improving the understanding of construction materials stocks and flows as it undergoes rapid urbanisation, population change and requires management of the resultant material demand (Nguyen et al., 2019; Nong et al., 2015).

In addition, the long-term vision for environmental sustainability means that knowledge of resource consumption is an essential component in the assessment of socioeconomic development plans. On a national level, for Vietnam, both the Sustainable Development Strategy for Vietnam (Socialist Republic of Vietnam, 2012b) and the National Green Growth Strategy (Socialist Republic of Vietnam, 2012a) present Vietnam's vision to adhere to sustainability principles. If such a vision is to be achieved, it is crucial that urban development planners consider where, and how, the raw materials required for construction are sourced in order to ensure sustainable and responsible supply.

Built up areas in the Hanoi Province have increased from 10% of the land area in 1970 to almost 23% in 2020. As shown in Fig. 1 built up areas now occupy ~670 km^2 (Novellino et al., 2021). In line with Hanoi's Masterplan to 2030 (Perkins Eastman, 2011) and current population trends this growth is expected to continue. Between 1990 and 2016 the percentage of Vietnam's population living in urban areas increased from about 20% to approximately 35% (General Statistics Office of Vietnam (GSOV), 2018). The population of Greater Hanoi has increased from 5.2 million in 2000 to 7.5 million in 2018 and is predicted to increase to 8.2 million by 2034 (General Statistics Office and United Nations Population Fund, 2016).

In order to accommodate a rising urban population, there are currently ambitious plans for urban development in Hanoi (Iwata, 2007; Leducq and Scarwell, 2018). More specifically, plans are already in place for a major new road network, new rail links, an expanded city core, five satellite urban areas and three eco-townships (Perkins Eastman, 2011). To meet these ambitious targets large quantities of raw materials are required. It is within the context of this planned urban development and the associated increasing demand for raw material supply that the current research has been undertaken.

In 2013 Vietnam was producing 105.7 million tonnes of sand and gravel annually and by 2019 was producing 185.5 million tonnes: an increase of 75.5% (General Statistics Office of Vietnam (GSOV), 2021), (Fig. 2). The effects of supply shortages have already made an appearance in Vietnam. Sand prices rose by up to 100% in 2017, due to supply bottlenecks related to the enforcement of environmental protection restrictions, required to prevent further damage to delicate ecosystems and productive farmland, and a clampdown on illegal mining (Viet Nam News, 2017). For example, sand mining in the northern provinces of Bac Ninh and Ba Giang have been suspended until an inspection of operations is completed. This is causing significant issues in construction project development as contracts have been agreed on lower prices and insufficient amounts of material are now coming onto the market. These price increases continue post-covid and construction sand costs have risen by 50% during 2021 (VN Express, 2021). In addition, many neighbouring countries, such as Malaysia and Indonesia, are following similar trajectories for continued economic growth and urban development, which requires access to raw materials. Sometimes these materials are sourced from other countries, thereby compounding supply issues within the source country. Competition for raw materials in South East Asia is unavoidable and has resulted in export bans of sand and aggregates by several countries (Marschke and Rousseau, 2022). This poses the risk of supply disruption if there is insufficient planning for access

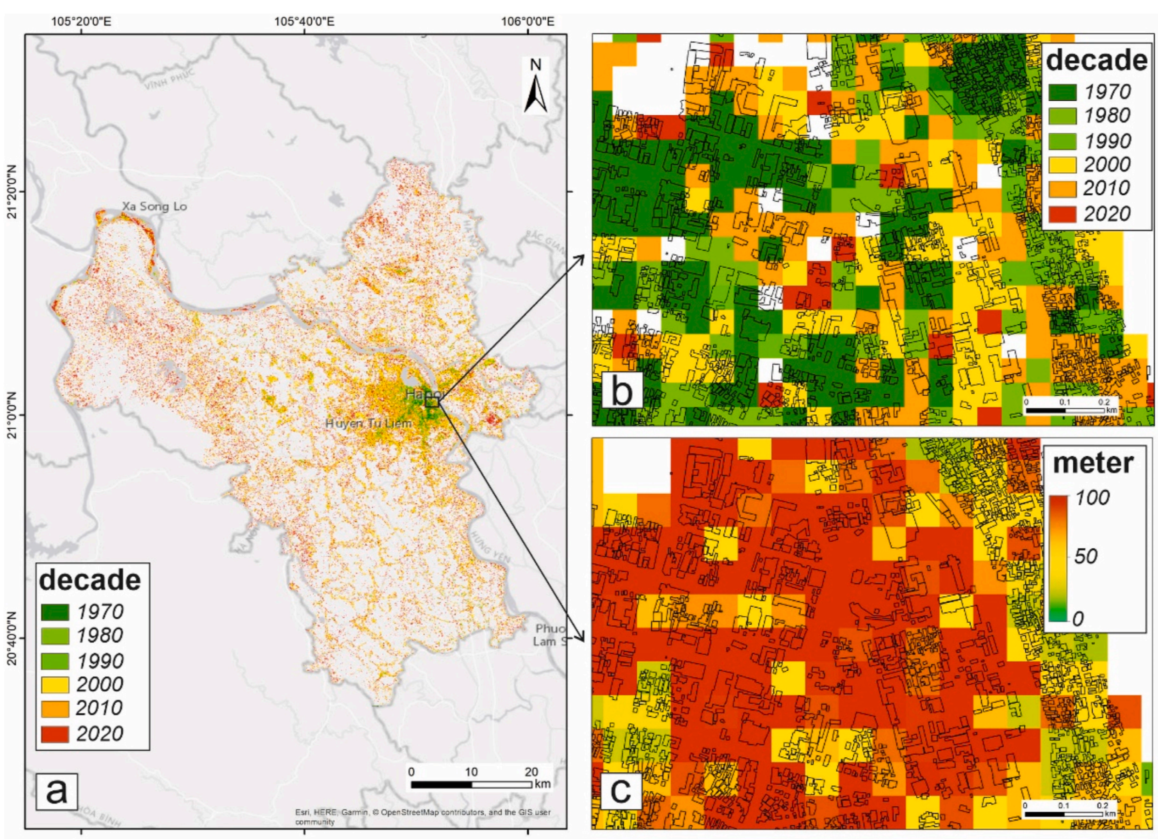

Fig. 1. Urban expansion within the Hanoi Region between the decades from 1970s until 2020s (a) using information derived from Novellino et al. (2021). (b) Detail of the building footprints derived from the GlobalMLBuildingFootprint database and construction years in the Hanoi city centre derived from Novellino et al. (2021). (c) Detail of the building footprints from the GlobalMLBuildingFootprint database (see Section 2.2) and height (m) from the World Settlement Footprint 3D dataset (see Section 2.2) in the Hanoi city centre. Administrative outlines ©OpenStreetMap contributors and the GIS user community.

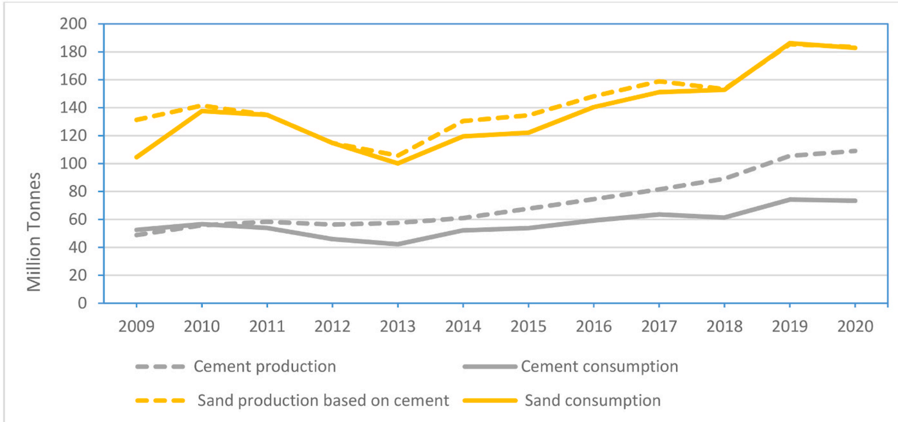

Fig. 2. Production and consumption of sand (estimated based on assumption of constant ratio between cement and sand consumption (see methodology) cement data due to lack of data (General Statistics Office of Vietnam, 2021; United Nations, 2021).

and use of raw material flows and stocks. This is not only an issue of concern at national level, but also at regional and city levels.

Therefore, for a megacity as Hanoi, such a study provides key information for planning and development of a strategy for the sustainable extraction of construction materials which underpins economic growth.

2. Dataset and methodology

This study integrates Material Intensity (MI) data (namely the average mass per unit of building volume) for building extracted from a review of literature data (see Section 2.1). We also collected the following information on the built-up areas and derived from EO (see Section 2.2): an inventory including building footprints, the transport network directions (a general term to include roads, railroads and subways), building height and building construction year (Fig. 3).

2.1. Collation of material intensity data for buildings and infrastructure in Hanoi

This study has only considered cement, sand, gravel and concrete (which itself will include the previous three materials). These materials are the largest consumed by volume (and often by value) in construction and have the greatest effect on the local area (as they are commonly sourced locally) which means they are the main cause of environmental/social issues resulting from unsustainable extraction within the urban hinterland (Gallagher and Peduzzi, 2019). Therefore, focus on these materials have the potential for the greatest socio-economic and environmental gains at a city level with regard to consumption of mineral resources. As such other materials commonly used in construction such as aluminium, steel, gypsum (for plaster) and sand in the form of glass, amongst other minerals have not been included in this study. Clay for brickmaking, like aggregates is a material extracted close to urban environments, however for Hanoi the volume of bricks used in construction is rapidly decreasing likely as modern construction techniques favour concrete (Novellino et al., 2021). Also, unlike sand, clay is not extracted from active sedimentary environments (i.e. rivers and beaches) which are under the greatest environmental threat from extraction of construction raw materials (Gallagher and Peduzzi, 2019). As a result, clay and bricks have not been included in our analysis.

The use of assumed, or measured material quantities in existing building stock in terms of MI, to assess composition trends is a well-established methodology (Marcellus-Zamora et al., 2016; Stephan and Athanassiadis, 2017; Tanikawa and Hashimoto, 2009). Commonly, such studies rely on detailed plans of urban development, which, however, may be non-existent or not readily available in many jurisdictions. MI is typically represented as kg/floor area (m^2), although in some occasions it may be kg/building footprint so care is needed when considering units. Converting between the two is simple if the number of floors and area of the building footprint are known. Calculation of construction material stocks is a relatively simple function of multiplication of the MI by the floor area of buildings (or, in the case of roads, surface area).

Several studies have consolidated existing literature into databases of MI for buildings of different types and different ages (De Wolf, 2014; Heeren and Fishman, 2019; Marinova et al., 2020). Such sources form an invaluable resource to enable an understanding of the composition of many building types. However as can be seen in the range of figures presented by these databases, great care needs to be taken when making assumptions and to ensure the most representative values are used.

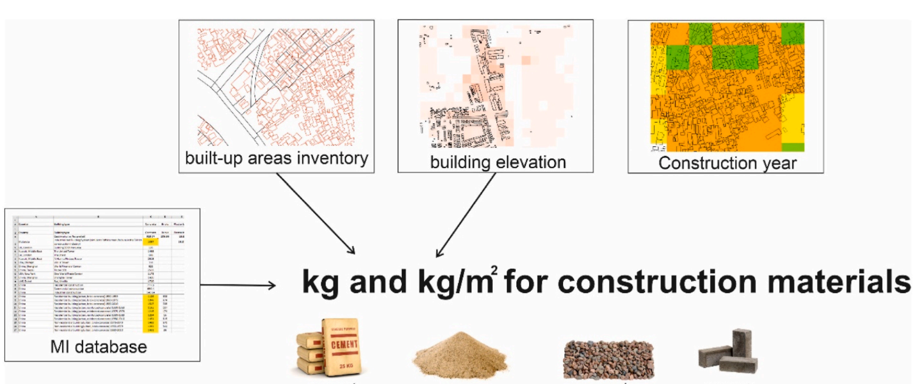

Fig. 3. Processing workflow employed for the bottom-up approach of this study to assess material stock. Details on data source, resolution, calculations, and validation are provided in Section 2.1 and 2.2.

Much of the range in these figures is due to differing construction practice and architectural styles. This is largely a function of building age, building purpose (i.e., domestic vs industrial) and the dominant architectural style in a particular geographic area. As a result, this study has only used figures that are most relevant to construction in Hanoi, which is mainly concrete modern residential apartments and office buildings. Figures for older and rural buildings and for geographic regions which may favour different architectural styles, such as Europe and North America have been discounted and emphasis is given to data from Asian cities, if possible, for southeast Asian countries similar to Vietnam in terms of urban development. This approach greatly reduces the number of studies that may be of relevance (most of which are from Chinese examples). Figures used in MI assumptions and associated references for this study are detailed in Table 1.

The range of materials reported on within relevant studies varies considerably. Some only report figures for concrete, whereas others report data for a full suite of building materials. Although concrete is a product of sand gravel and cement (and effectively double counts them to a significant degree) it was considered useful to include as it is commonly used in isolation as a metric for construction material consumption (Fernandez, 2007; Huang et al., 2018; Schiller et al., 2020). Also, the inclusion of concrete allows us to fill data gaps for the other three materials, as MI figures are not consistently reported.

This study has taken MI figures from relevant published data and calculated average values (based on the geometric mean due to the non-normal distribution of the data) and a range to indicate the likely spread of values (see references in Table 1). This range is necessary due to the numerous assumptions made and uncertainties in the data. We have used the 5th and 95th percentiles of the distribution of the data to give an indication of the likely higher and lower estimates. This is based on the reported material intensity values showing a wide distribution. Different sources have been used for concrete, cement and sand and gravel. This is a result of different studies reporting on different material. Additionally, this study has calculated a minimum value for cement, sand and gravel MI values based on the total concrete figure (using a split of 16.6%, 33.3% and 50% respectively – ratio of 1:2:3 for cement, sand and gravel) (The Concrete Society, 2022). The 1:2:3 concrete mix ratio provides the compositional ratio of the three concrete raw materials. This calculation appears to give values broadly in line with reported figures, However, it is not valid to reverse the assumption and use the same ratio and the MI cement, sand and gravel figures to calculate the concrete MI, as these raw materials are used in multiple other products and applications, for example in mortar or foundations, and, as such, will be a significant overestimate.

Clearly MI values will vary for different building types/architectural styles etc., however, without detailed site-specific data it can be very difficult to differentiate these. The MI values and divisions between building types and ages used by this study are outlined in Table 1.

In this analysis, we have not differentiated between residential buildings and commercial buildings (combining offices, industrial and other non-residential uses). The review of material intensities suggests that although this may be possible, with residential buildings typically having lower material intensities compared to commercial buildings, the difference between the two categories is not significant for a city-level analysis (Schiller et al., 2020). The relationship between residential and commercial buildings does not always follow a clear pattern and some studies show this relationship reversed, i.e. Fernandez (2007). A full breakdown of stock calculations based on the spatial and MI data can be found in the supplementary information.

MI data for road construction is somewhat simpler due to more commonality in road construction between different geographic regions and roads being constrained to a narrower set of standards when compared to buildings. However, variation still exists in reported figures and different road types will use vastly different quantities of construction materials. Such a range is not surprising considering the differences between a minor road and a highway, but highlights the care needed to choose correct values where undertaking city level analysis. As discussed below the available data for the transport infrastructure is available from an opensource dataset, OpenStreetMap (https://www.openstreetmap.org), that is very high-resolution (Barrington-Leigh and Millard-Ball, 2017). In order to ascribe relevant MIs to road types, this study has used the Vietnam Ministry of Construction standard specifications (Miatto et al., 2021). Ascribing such generalised values for the wide variety of road types defined by Open Street Maps to all roads in Hanoi will produce a large margin for error. However, these values are the most relevant for urban development. In addition, detailed MIs are not publicly available for all the different pavement types found in Hanoi. Data for the MI of rail infrastructure is taken from Han and Xiang (2013).

2.2. *Methodology for generation of the building and infrastructure stock*

For the building footprints we considered three open-source datasets: Global Building Footprint (GBF), World Settlement Footprint (WSF) and Google open Buildings (GOB).

- GBF is available worldwide (Microsoft, 2023) and produced combining Semantic Segmentation for recognizing building pixels on an aerial image using deep neural networks and polygonization for converting building pixel detections into polygons. The basemaps

Table 1
Estimated MIs for construction in Hanoi with indication of the geometric mean, 5th and 95th percentile values found from literature analysis on MI studies. For a full breakdown of figures used see supplementary information.

Building type	Age	Range	Material (kg/m^2 of floor area)				Source
			Concrete	Cement	Sand	Gravel	
Low rise	<1990	95th percentile	990	250	590	730	(Han and Xiang, 2013; Huang et al., 2013, 2018; Schiller et al., 2020)
		mean	960	180	410	550	
		5th percentile	930	150	310	360	
Low rise	>1990	95th percentile	970	230	660	750	(Fernandez, 2007; Han and Xiang, 2013; Huang et al., 2018; Schiller et al., 2020; Wen et al., 2015)
		mean	830	190	420	450	
		5th percentile	680	160	320	300	
High rise	<1990	95th percentile	1010	290	630	640	(Fernandez, 2007; Gao et al., 2020; Han and Xiang, 2013; Huang et al., 2013)
		mean	840	190	490	520	
		5th percentile	670	160	330	420	
High rise	>1990	95th percentile	1380	370	660	850	(Fernandez, 2007; Gao et al., 2020; Han and Xiang, 2013; Huang et al., 2013; Schiller et al., 2020; Wen et al., 2015)
		mean	950	220	440	630	
		5th percentile	680	160	320	490	

used in the GBF belong to Bing Maps and include Maxar and Airbus high resolution satellite imagery acquired between 2014 and 2021. In South Asia, the precision of the GBF is reported to be ~95% (Microsoft, 2023). We integrated the areas not mapped by GBF due to cloud cover at the time of the GBF production which totals a surface of ~740 km^2 using building polygons extracted from a Mask Region-Based Convolutional Neural Network (R-CNN) segmentation deep learning model (Stiller et al. (2019). The Mask R-CNN was trained using ~15,000 buildings from the GBF database itself and using the Google Basemap satellite imagery available in QGIS over the missing areas and acquired by Maxar and Airbus imagery between 2018 and 2019.

- GOB has been used to complement buildings not reported in the GBF which can be missing small buildings in rural areas. The GOB dataset has been produced by Google via a U-Net model on high-resolution satellite imagery provided by Maxar Technologies and CNES/Airbus (Google, 2023; Sirko et al., 2021). We used inference carried out during August 2022 where GOB has a confidence score of 0.81 over Hanoi (Google, 2023; Sirko et al., 2021). In GIS, we spatially merged the GBF and the GOB datasets and finally dissolved the overlapping areas. These building footprints were filtered considering the landcover maps and NDVI (Normalized Difference Vegetation Index) values for the corresponding years. Landcover maps are the ones produced with Sentinel-2 datasets in Novellino et al. (2021), they allowed to mask out polygons within water bodies and polygons labelled as forest areas or with a high NDVI value. We validated the remaining footprints against approximately 300 manually polygonised buildings over a test area against ~300 manually polygonised buildings.
- WSF 2019 has been produced by the German Aerospace Center in collaboration with Google Earth Engine (Marconcini et al., 2021). WSF provides a 10m resolution binary mask outlining the extent of human settlement globally (not the buildings footprint) derived by means of 2019 multitemporal Sentinel-1 and Sentinel-2 images. The map has an accuracy of approximately 84% (Esch et al., 2022). We used this map as an independent check for the extent of the built-up areas extracted from the land cover maps and the building footprints of GBF and GOB. Specifically, the overlapping area of the building footprints between our dataset and WSF 2019

In order to calculate the change in building stock and MI through time, the age of buildings has been analysed by decade by intersecting the building footprints with the land cover maps produced in Novellino et al. (2021) and covering the period 1975–2020. Additionally, building heights were assigned to the polygons using the World Settlement Footprint 3D dataset, which includes the average mean height of buildings within a 90m grid using Sentinel-1 and Sentinel-2 satellite imagery in combination with digital elevation data and radar imagery collected by the TanDEM-X mission (Esch et al., 2022). Building volumes were then derived.

We extracted information on the transport infrastructure from Open Street Map (OSM) data which is available for free at https://download.geofabrik.de (OpenStreetMap contributors, 2022), and contains information on the path and category (e.g., railway, road network) at different levels (e.g., from pedestrian paths to highways and subways) updated as of December 2022. Such information is provided by a community of voluntary mappers using aerial imagery, GPS devices, and low-tech field maps and was completed between 60% and 80% in 2016 for Vietnam (Barrington-Leigh and Millard-Ball, 2017). We extracted the surface area covered by each category of roads based on the width of the empirically derived from a visual analysis of the dataset: e.g., an average width of 30 m for primary roads and motorways and 3 m for railways (for a full list please refer to supplementary information). For the purpose of this analysis, the OSM data has been generalised into three categories for the transport infrastructure: surfaced roads (including subways (underground walkways), considered equivalent to surfaced roads regarding MI), unsurfaced roads, (including walkways/cycleways which are considered to be equivalent to unsurfaced roads regarding MI) and railways. As no information is available on the material composition based on different ages, we did not consider the time factor for the transport infrastructure.

Data regarding the land use classification for urban infrastructure is calculated in km^2 for ease of integration with the average and range of MI data measured in kg/m^2. Integration of building height data with MIs was achieved by calculation of the number of floors for any given building, then multiplying the number of floors by the building area to gain the total floor area, which then can be simply multiplied by the MI. The number of floors has been calculated using average typical floor heights as reported by Evans et al. (2019). Therefore, every building below 4.5 m was considered to be single storey and every 3.2 m above this added an extra storey (see supplementary information for detail on how storey numbers have been calculated).

3. Results

In our study area, built-up surface covers ~680 km^2 which includes ~1.4 million building footprints. However, the building footprints only accounts for ~30% of the built-up area since small buildings next to each other are currently not captured by all the three datasets.

Considering the area covered by transport network systems (37% of the built-up surface) and the construction, mining and dump sites (4% of the built-up surface), we believe building covers ~59% of the built-up surface. The area does include the floor area of the buildings, not multiple floors. This value is almost matching the area of buildings given by the WSF, which account for 62% of the built-up area.

We then analysed information on building area, construction year and height only for the building for which this information were available (~52% of the total). As supported by the time series analyses of land cover and land use change in Novellino et al. (2021), most of the post-1970 building stock (excluding transport infrastructure) was built during 2000s (~27%). This will be an underestimate as it will not take into account demolition and redevelopment of previously developed land. In terms of area covered, small buildings are dominant: almost 98% of the total building stock has an area ≤1,000 m^2 and just 0.02% are >10,000 m^2 (Fig. 4b). The distribution of the building area is slightly decreasing over time with the median value of the building area orbiting around 100 m^2.

In terms of height, around a quarter of the building stock is ≤ 3m (based on the average gridded data from the world settlement footprint) which corresponds to a one-storey building. The built-up area analysis shows that most of the buildings within the Hanoi Province are small single-story dwellings, typical of the building stock in many cities at a similar stage of development (Mahtta et al., 2019; Tripathy et al., 2022). The distribution of the building height has decreased over the different construction periods with the only exception of 2000s (Fig. 4c).

Most of transport network within the Hanoi Province is dominated by tarmac-paved (surfaced) roads (~90%), followed by unsurfaced (~10%) while railway and subway have a cumulative coverage of <1%.

The integration of the MI data with the land use classification results enables the quantification of the total stocks of building materials contained within urban infrastructure (building stocks and transport infrastructure) in Hanoi (Fig. 5). Unsurprisingly, given the size of Hanoi, this is a considerable quantity of material (around 600 million tonnes) (Fig. 5). For comparison the average quantity of sand and gravel contained in the in-use building stock and transport infrastructure is equivalent to around half the entire Vietnamese national production in the last 10 years (General Statistics Office of Vietnam (GSOV), 2021). These figures provide an indication of the total urban stock (buildings and infrastructure) in Hanoi, which would have been constructed at different times, but without high resolution temporal imagery data, it can be difficult to estimate demand figures associated with new construction for recent years. However, by considering land use change

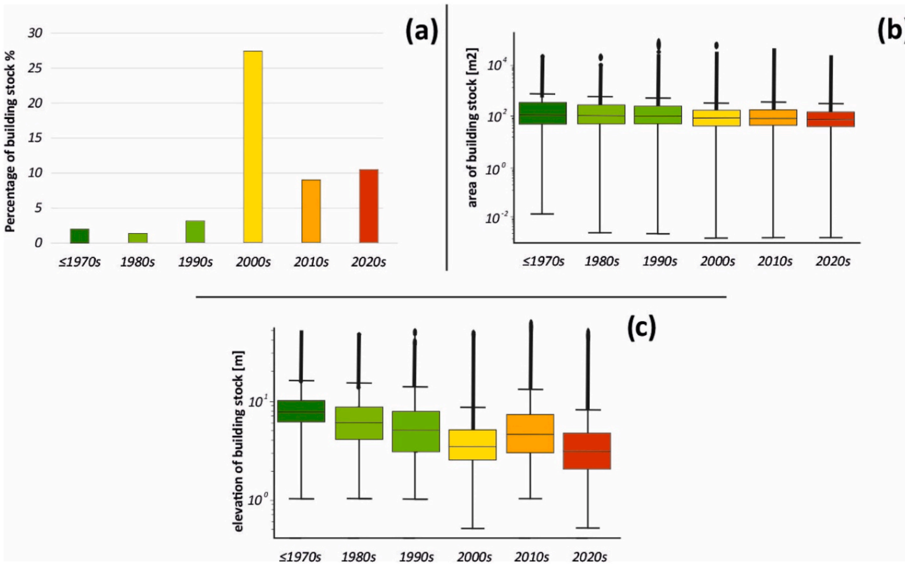

Fig. 4. Diagrams showing the distribution of the 52% of the total building stock for which information were available: percentage of total area of building vs the construction decade (a), area of the building footprints in logarithmic scale vs the construction decade (b) and height of the building in logarithmic scale vs the construction decade (c).

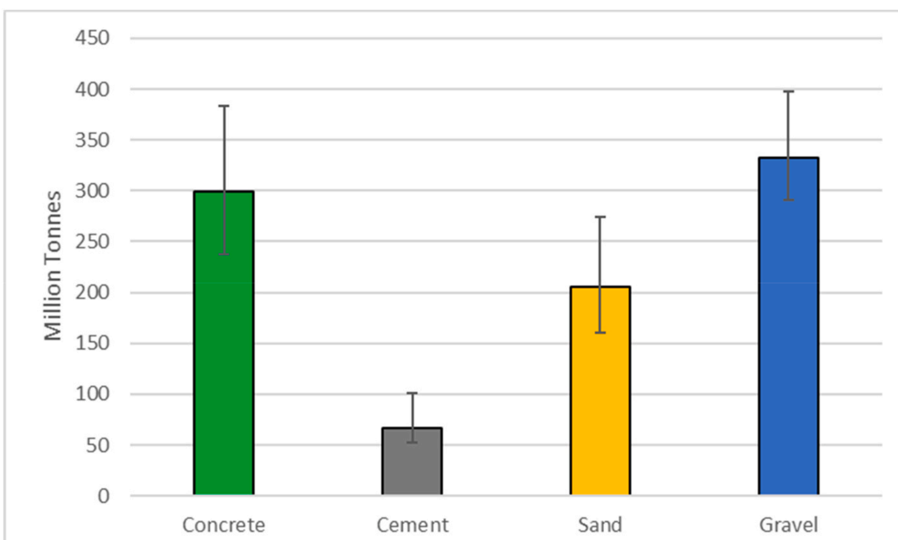

Fig. 5. Total material stocks in urban infrastructure for Hanoi showing 5th and 95th percentiles (lower and upper bars).

analysis conducted on lower resolution satellite data (decadal) (Novellino et al., 2021) it can be seen that the main period of urban growth in Hanoi begun in 2000, and the urban area has doubled in size since 1975. Correspondingly the building stocks began to increase from the 1990s onwards and increased by 50–60% by the 2020s. As a result, it is likely that much of these stocks is contained within relatively new buildings and infrastructure. This is confirmed by the temporal analysis conducted in this study showing how total stocks changed very little between the 1970s and 1980s, but during the 1990s onwards building material stocks have undergone constant growth (Fig. 6). This trend is likely to be the significant development of new high-rise buildings, which rose between 1990 and 2000 (50% more concrete used to construct high rise building during this time period compared to the previous decade). The number of new high-rise buildings then actually slightly decreased in the following decades, suggesting a move towards low rise urban development. As noted in the discussion, this method will not differentiate refurbished and replacement of existing buildings, however, as most of Hanoi's development is less than 30 years old this is unlikely to constitute a major proportion of development.

This analysis also gives the total stocks as they occur in different construction types (Fig. 7). This shows that the majority of construction material aside from gravel, due to its heavy use in transport infrastructure, is contained in high rise (>1 floor) building types. This is despite single structure buildings dominating the area (Fig. 4).

These data can give a crude but important figures on the quantities of construction materials that will be required if Hanoi is to continue with its planned growth (Fig. 8). Dividing the total area by total stocks in 2021 shows for every new km^2 of urban infrastructure around 520,000 tonnes of concrete are required, or 360,000 tonnes of sand, 580,000 tonnes of gravel and 115,000 tonnes of cement.

The results from this methodology can also be viewed spatially. The spatial distribution for construction materials appears to reflect the population and infrastructure density within each district. We summarised the results by district level this being the key entity used for

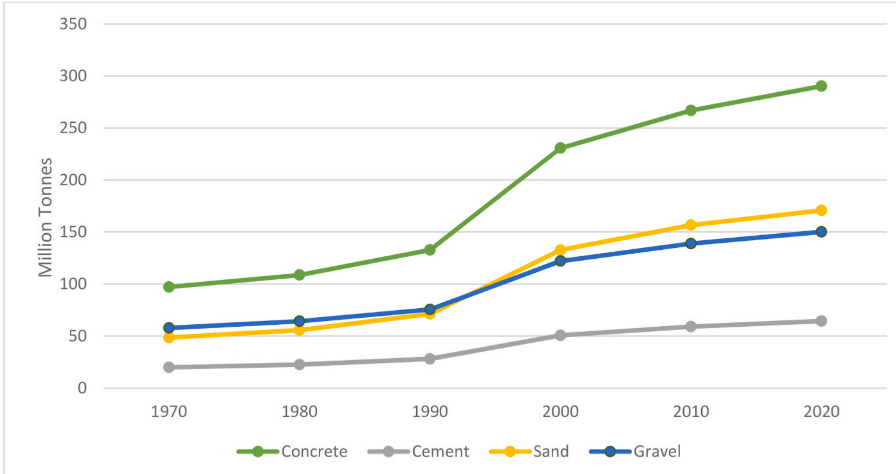

Fig. 6. Cumulative stocks of urban infrastructure by material over time, concrete will include a proportion of cement, sand and gravel.

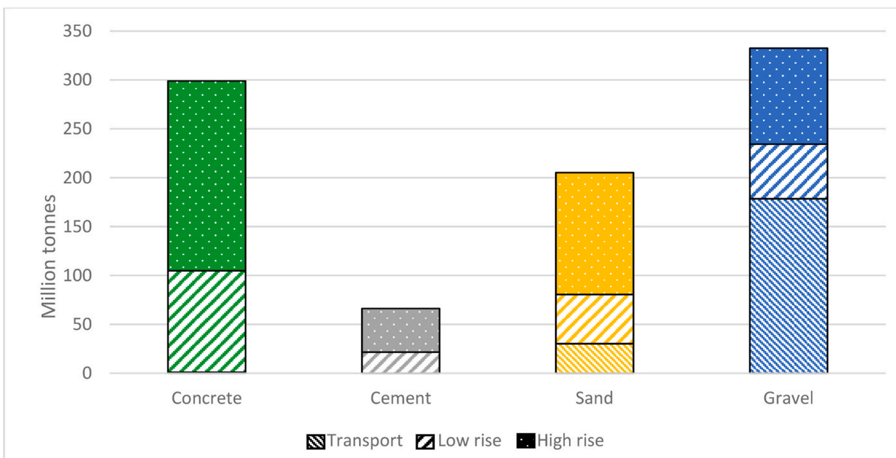

Fig. 7. Total stocks of urban infrastructure by construction type in 2021.

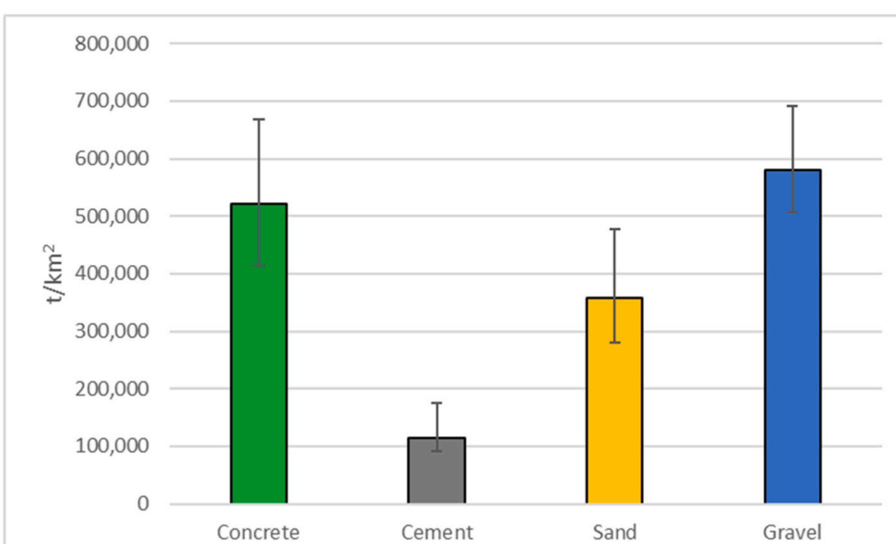

Fig. 8. Mass of material required per area (t/km^2) showing possible range (5th and 95th percentiles and geometric mean), using 2021 as a baseline.

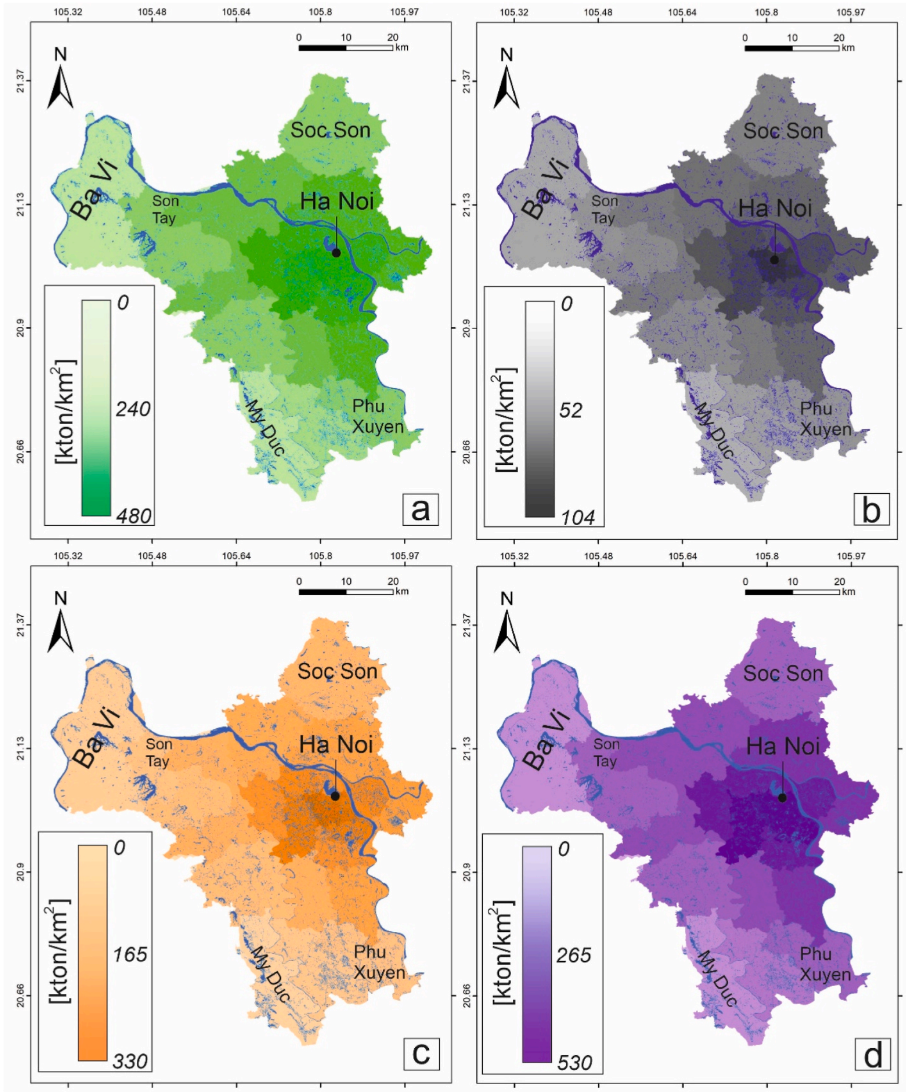

Fig. 9. Stocks per area for built infrastructure by administrative regions across the Hanoi Province as of 2021: concrete (a), cement (b), sand (c) and gravel (d). Administrative outlines ©OpenStreetMap contributors and the GIS user community.

urban planning. The Hanoi city centre is the area with the highest density of construction (Fig. 9). Density of construction materials such as cement and gravel are 2–3 times higher in the central districts than the rural districts of the Hanoi Province.

4. Discussion

Rapid urbanisation is material intensive and can lead to material supply challenges, environmental implications and unsustainable construction practices. The methodology developed by this study has the ability to rapidly build a powerful dataset of the urban stock (buildings and infrastructure) of a city or administrative regions (Fig. 9) and its changes over a range of timescales. Although building footprint and height data are in effect a static snapshot, land use change data from satellite imagery provides a time series over a range of resolutions. Unlike other similar studies discussed previously the presented method can be applied using freely available satellite data, does not rely on difficult to access urban planning and construction industry data and can be used to monitor the growth of building stock over time. This can be used to understand the land use implications of urban development, to develop predictive models of secondary material availability at the end-of-life, and to assess material consumption associated with urban expansion. Therefore, the method we present can be replicated anywhere over any time span for which EO and material intensity data are available. The EO-derived data can be updated regularly, offering the ability of future exploration into spatiotemporal dynamics of material stocks and, more importantly, offer a good trade-off in terms of resolution and area covered to support policymakers in urban planning i.e. Wen et al. (2015) and Abd Rashid et al. (2017) Some caveat remains in the ability of the EO datasets to capture small buildings placed next to each other (see Section 3).

In the case of Hanoi this method allowed us to quantify the urban material metabolism over the past 50 years using concrete, cement, sand and gravel as the reference construction materials. The results suggest a steep increase in material consumption from 1990 onwards, which relates to the construction of high-rise buildings, but also the expansion of construction in the Greater Hanoi. Using the tonnage per km^2 required for new urban infrastructure in Hanoi calculated by this study indicative figures of the approximate amounts of material that may be required for achieving the Hanoi Masterplan can be estimated. For instance, if the satellite towns of Hoa Lac, Son Tay, Xuan Mai and Sac Son are to be fully developed before 2030, as stated in the Masterplan, an additional 204 km^2 of urban areas will be built (Perkins Eastman, 2011). Using this area and the tonnage per km^2 estimates shows this development will require approximately 106 million tonnes of concrete or 73 million tonnes of sand, 118 million tonnes of gravel and 24 million tonnes of cement. This will require production of nearly 20 million tonnes of sand and gravel per year, nearly 10% of the total annual national production (General Statistics Office of Vietnam (GSOV), 2021).

When compared to the total stocks created in previous decades the scale of the increase in demand for the next 10 years can be readily appreciated (Fig. 10). Such levels of demand will be difficult to source from the existing supply chain, which is already under considerable pressure (VN Express, 2021).

It is evident that sourcing of materials to meet the planned demand has not been factored into the planning process, a situation not unique to Hanoi. Our methodology, which allows for rapid assessment of material in building stock, provides an approach for consumption and production monitoring at a city level to address data gaps required for the urban planning and development process.

The tonnage per km^2 for urban infrastructure, as calculated by this study have significant error margins (due to assumptions with MI quantities, a range of different building styles/ages/types incorporated etc.) and this is reflected by the range of values given in Figs. 5 and 8. These are estimates based on broad building typologies. If enhanced data on local building methods, architectural styles and bills of quantities for local projects were available, then the error range in the results may be substantially reduced. Our analysis highlights the significance of this data gap, which contrasts the resolution of available satellite data and open-source mapping data that is considerable and under continuous improvement.

4.1. Comparison with other studies

Similar studies on different case studies have yielded comparable results, although differences are apparent due to their geographical extent and regional coverage. For example, Gao et al. (2020) estimated the total buildings stock (predominately concrete) in Shanghai to be around 900,000 t/km^2 in 2015. In our study the estimated total stocks are around 1,050,000 t/km^2 (sand, gravel and cement) and 520,000 t/km^2 of concrete. This indicates that the development of Hanoi may be similar to Shanghai, demonstrating a similar trajectory in urban metabolism influenced by the considerable stock of high-rise buildings. A similar analysis has also been undertaken for Hanoi, which attempts a bottom up MFA and quantifies future demand for aggregates, however, using planning data not available in the public domain (Schiller et al., 2020). This came to similar conclusions to this study with demand (for over 400 million tonnes of construction material by 2030) far outstripping supply.

This bottom up approach for calculating potential demand can be compared with a top down approach, for example as taken by Novellino et al. (2021), where consumption of building materials to fulfil the requirements of the masterplan was estimated using population changes and production statistics. An estimated 200 million tonnes of sand and gravel, 400 million tonnes of crushed rock and 60 million tonnes of cement would be required to meet the aims of the Masterplan. Whilst the figures calculated by this study for sand and gravel and cement are broadly comparable (191 million tonnes and 24 million tonnes respectively) there is clearly a significant difference in the crushed rock (this will be incorporated into the gravel figure considered by this study). This is possibly due to significant volumes of fill materials for land reclamation and landscaping not being incorporated by this study which has been focused on buildings. Additionally, it highlights the lack of certainty in mineral production statistics, especially for sand, and the large projected errors associated with these figures, as discussed in Novellino et al. (2021).

In another study that focused on transport infrastructure, Miatto et al. (2021) estimates the stock of sand and gravel in roads in Greater Hanoi as 9.7 million tonnes and 64 million tonnes (for 2016) respectively. Our study calculated total stocks of sand at 30 million tonnes, gravel at 180 million tonnes (for 2021). Such a significant difference in sand stocks is likely due to.

- The different time spans and the input datasets analysed, 2010–2016 in Miatto et al. (2021) and 2020 for the data used in this work.
- The classification of road types, Miatto et al. used detailed plans as well as input from local experts, whereas this study relied on third party data for road types and their likely compositions. Good practice likely would combine aspects of both methods, using expert local judgment as well as easily accessible earth observation datasets.

Another important consideration when comparing with other studies is the calculation of average material intensities, which requires a great deal of assumptions. MI figures can vary by orders of magnitude as can be seen by values for a range of sky scrapers in De Wolf (2014) where concrete values range from 125 kg/m^2 to 1,723 kg/m^2. Such differences may be expected in buildings with significant differences in architecture, but even more 'typical' building styles can show a wide range. For instance, Wen et al. (2015) shows how the use of prefabricated concrete versus cast in situ buildings can increase the material intensity by 40%.

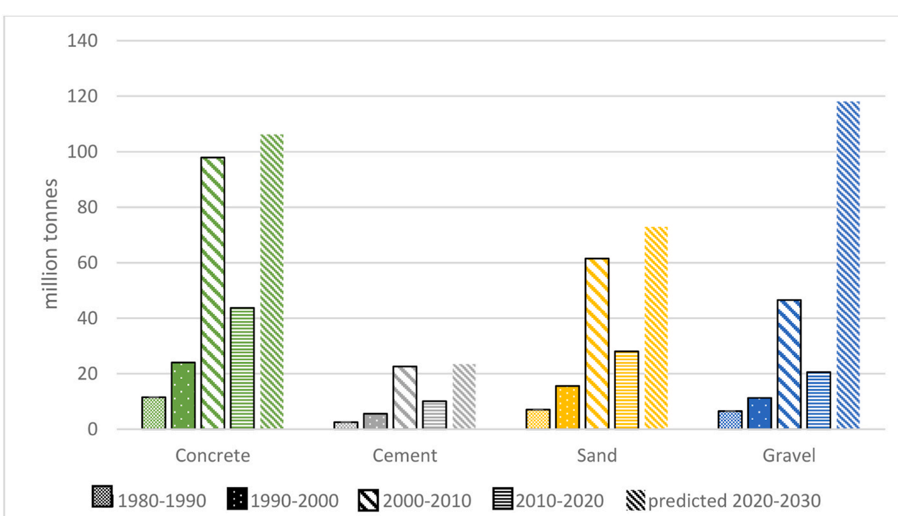

Fig. 10. Comparison of building stocks created over the last five decades and those predicted to be required for the next 10 based on the area of planned urban development in Hanoi.

Some studies, such as Abd Rashid et al. (2017) also report figures that differ considerably from the averages calculated by this study, for example on the MI for typical row houses in Malaysia that appear to use over twice the expected amount of concrete. This is likely to be the result of different metrics being used, i.e. the inclusion of associated infrastructure. This demonstrates that care is required when calculating typical material intensities to ensure direct comparisons are made.

4.2. Implications for recycling of construction materials

This study shows that a large (and growing) quantity of construction material is contained with the existing building stock in Hanoi that will be available for recycling at some point to alleviate the pressure on virgin resources. However, as demonstrated by the times series analysis in Fig. 4 stocks of construction materials are primarily in new urban infrastructure which will not be available for recycling for many years. The life of a building will be dependent on architectural and planning factors, but it is estimated to vary between 20 and 40 years (based on Chinese examples) (Gao et al., 2020; Miatto et al., 2017). As a result, much of the building stocks in Hanoi will not be available for recycling until after the Masterplan period of up to 2030. Therefore, recycled aggregates are unlikely to make a significant contribution for the planned period and are therefore not a viable alternative to virgin production in the near term. The quantitative assessment of this study suggests that once the building stock in Hanoi begins to mature there will be a considerable amount available for recycling. This should be planned into urban growth strategies at the earliest opportunity to ensure recycling of construction materials is an established part of the supply chain.

4.3. Future development

This study gives a high-level time series analysis of the changes in building stock over decadal time ranges over an area where a significant gap in yearly aggregates mineral data on production and consumption is acknowledged, as noted by UNEP (Vander Velpen et al., 2022). It is exceedingly difficult in many countries to estimate production of sand and gravel due to the informal nature of the industry and traditional data collection methods of industry surveys are expensive and unrealistic (Carabassa et al., 2020; Rohizan et al., 2021; Smigaj et al., 2022).

It may be that spatial analysis for changes in building stock with a high temporal resolution (annual) may be able to calculate consumption of construction minerals, which can be used as a proxy for production. Such analyses (which would require high-resolution satellite imagery that may not be open access) would allow for more detailed analyses of the consumption patterns of materials, by estimating changes in annual use for the land use classes specified in this study. An example of this approach is seen in Miatto et al. (2021) where time series data is used to analyse the annual consumption for building materials used in transport infrastructure. With regard to increasing the use of secondary aggregates from recycling it would also be possible to undertake an in-use stock calculation and combine this with lifetime distribution to estimate the outflow to end-of-life. Additionally, this is a scalable methodology which in this study has focused on a city scale but due to the ease of access to the data there is no reason why it could not be scaled to a regional or country scale.

5. Conclusions

In 2015, the Vietnamese government approved the ambitious Master Plan for the urban transport system of Hanoi towards 2030, with a vision to 2050. However, there was no detailed quantification of the material requirements of the proposed infrastructure. This study has developed a methodology to calculate city level building stocks, with a focus on concrete and aggregates, over decadal timescales using freely available satellite data. We have used this to examine the stocks of construction materials in Hanoi urban infrastructure. This shows (unsurprisingly) exceedingly large tonnages of sand, gravel and cement contained within Hanoi. Analysis of the age of buildings show that the volume of materials contained within building stock is rising and is projected to rise further. This is of great concern as local sources of construction material, especially sand and gravel, are already under great pressure and traditional sources are severely depleted or are causing significant environmental impact due to over-extraction (in the case of sand extraction from local river systems).

The material demand in Hanoi will increase further as more investments are mobilised and large-scale construction projects take place to develop Hanoi's satellite urban areas. Our assessment has shown that for every new km^2 of urban infrastructure approximately 520,000 tonnes of concrete, or 360,000 tonnes of sand, 580,000 tonnes of gravel and 115,000 tonnes of cement are required. If the Hanoi Masterplan is to be achieved by 2030, then the material demand is likely to be for 106 million tonnes of concrete or 73 million tonnes of sand, 118 million tonnes of gravel and 39 million tonnes of cement. This would equate to approximately 20 million tonnes of sand and gravel production per year from local sources. In principle, the demand is likely to be higher, as our modelling work did not account for the material requirements of maintenance activities for existing and future roads and railways. To limit the negative consequences of rapid development, Vietnam's policymakers are recommended to take stock of the current levels of demand, and plan accordingly. For example, by employing policy measures such as mandating a minimum recycled content for construction materials, increased use of manufactured aggregate to replace sand, encourage alternative sources to river dredged sand and to take informed decisions to reduce the potential negative impacts on the natural environment and, ultimately, the people.

One potential future application for the methodology developed by this study is to integrate high resolution satellite data over annual timescales, to calculate annual consumption of sand and gravel. Such statistics are noted by UNEP as a major barrier to the sustainable development of sand resources, and a significant global challenge. This data could further be improved by better understanding the MI of buildings currently under development in Hanoi, as well as the building typology, construction methods and variance in building materials and architecture over time.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Building footprint data has been provided from Global-MLBuildingFootpint and licensed by Microsoft under the Open Data Commons Open Database License. This database is made available under the Open Database License: https://opendatacommons.org/licenses/odbl/1.0/

Building height data have been taken from the World Settlement Footprint 3D through the German Aerospace Center (DLR). At present, this data is available on request from DLR (contact: guf@dlr.de).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2023.100109.

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