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Case Report

Method for Quantifying Supply and Demand of Construction Minerals in Urban Regions—A Case Study of Hanoi and Its Hinterland

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Abstract: Urbanization is a global trend: Since 2007 more than 50% of the world's population have been living in urban areas, and rates of urbanization are continuing to rise everywhere. This growth in urbanization has led to an increased demand for natural resources, in particular non-metallic minerals such as stones, sand and clay, which account for one third of the entire flow of materials. Generally, these materials are traded within regional markets. This close geographical link between the demand for building materials in urban areas and the material supply in the hinterland leads to massive interventions in the natural environment and landscape. These urban–rural linkages can be revealed by applying Material Flow Analysis (MFA) to the built environment in order to trace the flows of building materials. The objective of this paper is to present a method for quantifying regional material flows by considering the supply and demand of building materials. This will be applied to the Vietnamese case study area of Hanoi and its hinterland province Hoa Binh. The results indicate a consumption of almost 60% of the construction mineral reserves in total secured by planning in the hinterland province considering a period of 15 years. However, this does not allow for the general conclusion that raw materials are sufficiently available. The sand reservoirs are only sufficient for eight years and clay reserves are used up after four years. This increases the need to exploit further raw material reserves, which are becoming increasingly scarce and results in stronger interventions in nature In order to safeguard the hinterland from the negative impacts of urbanization, a new understanding of resource efficiency is needed—one that acknowledges both resource efficiency in the construction of urban structures and appropriate resource conservation in the provision of the raw materials from the hinterland. This will require the creation of new integrated planning approaches between urban and regional planning authorities. Regional MFA is one way of realising such an approach.

Keywords: Regional Material Flow Analysis; urbanization; hinterland; building materials; supply and demand; mining; built environment; integrated planning

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1. Introduction

The year 2007 saw a new milestone in mankind's development when, for the first time, a larger proportion of the world's population lived in urban than in rural settings. Today the process of urbanization is ongoing: In particular, those countries of Asia and Africa with a low level of prosperity are undergoing a fast process of urbanization [1]. In Vietnam, urban areas contribute around 70–75% of the country's annual GDP. For this reason, one major goal of the Vietnamese Central Government is to promote and support urbanization [2].

The link between urbanization and the demand for building materials has often been highlighted [3–5]. Non-metallic mineral-based products such as concrete, asphalt, bricks, stones and aggregates make up about 94% of global stocks of building materials [6]. Within these material groups, the most significant raw materials are non-metallic minerals such as stones, sand and clay, which are mainly used in buildings and urban infrastructure.

As high-volume, low-value products [7], bulk non-metallic building minerals are relatively expensive to transport [8]. Thus they are generally traded in regional markets with maximum transport distances of about 50 kilometers [9], ensuring a close physical link between the urban consumption and rural supply of these materials. Today we can observe a worrying trend, namely that the hinterland of rapidly urbanizing areas is either running out of non-renewable natural resources or is facing serious environmental problems. Several Asian countries are already experiencing a severe shortage of natural river sand [10] and are struggling to cope with the devastating consequences of mining activities such as diverted river courses, an increase in suspended sediments and erosion [11]. Clays are often extracted from topsoil, thereby harming fertile farmland [12]. The extraction of limestone and basalt can ravage landscapes, degrade ecosystems and destroy natural habitats [13,14].

Hence, we urgently need an understanding of urban–rural linkages in regard to the supply and demand of building materials. The few previous studies which have applied Material Flow Analysis (MFA) in an urban–rural context have done so with regard to the supply of cities with food and energy [4]. With regard to construction materials, some papers have considered mining activities in the hinterland of urbanized areas in order to discuss land-use conflicts between growing settlements and mining areas [15]. However, these did not attempt material flow calculations und thus do not directly address links between urban consumption and rural material supply.

So the next question is whether approaches are already available to bridge this gap. There exist a number of MFA concepts suitable for analysing physical flows of material to and from the built environment (see, e.g., [3,16–18]). Current approaches are either derived from macroeconomic statistics following a deductive approach (top-down) or extrapolated from data on elements of the built environment (bottom-up) [18]. Top-down approaches, however, cannot provide a precise classification by type of material and can hardly distinguish between different elements of the built environment such as buildings and roads (e.g., [19]). By contrast, bottom-up approaches supply more detailed information on materials as well as better spatial differentiation, thereby offering a good empirical basis for practical discussions of stakeholders (e.g., [9]).

Due to the described characteristics of the bottom-up approach, it can be recommended as a basis for the development of a method to quantify regional building material flows. This approach enables the consideration of concrete spatial references as well as a differentiation of material categories, which will allow links to be established between building material categories of material demand and raw material categories of supply. In this paper we apply the bottom-up MFA approach to the built environment of urban regions. In this way we determine the demand for building materials in defined regions. To this we add an approach to describe the supply of raw materials needed to provide the building materials. For this purpose, we use a method that has been introduced and recognized in mineral planning. We simulate the link between supply and demand considering supply relationships as are evident from official documents of the regional raw material supply. To concretize the method we use as our case study the urban region of Hanoi in Vietnam.

The analytical concept and dataset are described in Chapter 2. The results of applying bottom-up MFA to data from the urban case study region are presented in Chapter 3 and discussed in Chapter 4. Here we consider methodological aspects of quantifying material flows, in particular their impacts on urban–rural linkages and the associated uncertainties. In the final chapter we draw some conclusions on how integrated approaches can help ensure the sustainability of urban regions.

2. Methodical Approach and Dataset

2.1. General Concept, Terms and Definitions

The spatial distribution of the demand and supply of mineral building materials can be simply illustrated as a ring-shaped structure (Figure 1a). At the core are the urban areas that demand such bulk materials for the construction and maintenance of buildings and infrastructure. Around this core is the regional hinterland, whose mines provide the raw materials for the production of these materials.

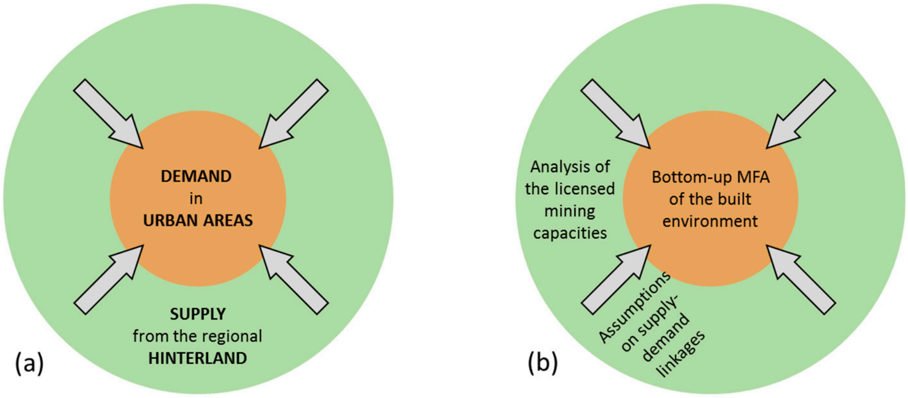

Figure 1. (**a**) General concept for the spatial distribution of supply and demand of regionally traded bulk mineral building materials; (**b**) overview of the analytical method.

The demand for construction materials is induced by the dynamic of the construction activities of buildings and infrastructures (roads). These elements of the built environment consume most of the non-metallic construction materials [18]. The required construction materials or inflows into the stock, respectively, are calculated using the method of stock driven dynamic bottom-up MFA [3] (see Sections 2.2 and 2.3).

The basic bottom-up MFA principle is to multiply some practical measure of the stock or flow of interest by indicators for characteristic material compositions (MCIs) that describe the relative material content of the considered good [20]. The inductive principle behind this analysis offers great flexibility with regard to the spatial delimitation of the investigated area as well as the material classification of results [18]. Figure 2 summarizes in general terms how this principle is applied to the considered elements of the built environment (see "stock calculation principle" and in detail 2.2.1.ff.).

"Stock driven" means that flows result from stock changes. The term "dynamic" indicates that the MFA is covering several periods [3]. Thus we implement the dynamic aspect by calculating flows based on changes of stocks in the period under study (2015–2030), which corresponds to average planning periods in the case study area. The calculation is based on the following principles: We calculate the annual stocks and determine the differences of the stocks of successive years. The "stock-driven" inflows are calculated from these differences plus the inflows resulting from the replacement of demolished buildings and renovation roadworks (see Figure 2 "Dynamic Calculation Principle" and in detail 2.2.1 ff.).

Typologies	**Stock Calculation Principle**					**Dynamic Calculation Principle**						
Construction Elements within the Building and Infrastructure stock	Particular Measure for stocks		Specific Material Quantity		Absolute Material Quantity	Material Stock t2		Material Stock t1		Additional Stock change (period t1-t2)		Demand (period t1-t2)
Domestic buildings (DB)	Floor area [m²]	x	MCI [kg/m² floor area]	=	Material Stock in DB [kg]	Material Stock in DB t2 [kg]	-	Material Stock in DB t1 [kg]	+	Material Stock (DB) Replacement t1-t2 [kg]	=	Inflow (DB) t1-t2 [kg]
Non Domestic building (NDB)	general surcharge on domestic buildings [%]			=	Material Stock in NDB [kg]	Material Stock in NDB t2 [kg]	-	Material Stock in NDB t1 [kg]	+	Material Stock (NDB) Replacement t1-t2 [kg]	=	Inflow (NDB) t1-t2 [kg]
Road classes/ Pavement types (PT)	Road (R) surface [m²]	x	MCI [kg/m² R surface]	=	Material Stock in Roads (R) [kg]	general assumptions based on construction rates, renewal rates and "construction sector relationships" [%]					=	Inflow (R) t1-t2 [kg]

Figure 2. Implementation of the bottom-up Material Flow Analysis (MFA) calculation principle and the "dynamic stock-oriented" specification of the principle to elements of built environment.

Regional supply of building materials is defined by us as the stock of raw materials in the regional hinterland available for the production of the building materials, for which has a valid planning permission for extraction exists (see Section 2.4). This follows the general understanding of raw material reserves as frequently adopted in international discussion [21].

We define the provincial hinterland as immediately adjacent to the metropolis, operationalized by assuming short delivery distances for mass building materials. This is caused by special properties of these materials [9]. Non-metallic building materials in bulk represent a high-volume but low unit value [22]. Moreover, the materials are affected by high relative transport costs [8]. Available studies therefore assume that transport distances for such materials generally do not exceed 50 km [22,23]. The term hinterland was introduced in Human Geography in 1889 by Chisholm who used hinterland to refer to the area inland from a cost marked by ports used for exports and for imports [24,25]. Urban geographers use the term urban hinterland when referring to metropolitan tributary regions that are closely tied to the central city [26]. The concept of the ecological footprint focuses on the supply function of the hinterland for cities when using this term. Kissinger and Haim, e.g., distinguish between local and global hinterland in this context [27]. This understanding of local hinterland comes very close to the understanding of the term used in this study, whereby we define "local" by the limited distances of transport described above.

However, the analysis only considers one part of this hinterland, which provides a certain proportion of the material supply required by the metropolis. The determination of this proportion is based on information from local planning authorities and documented in available planning documents [28]. Figure 1b gives a visual overview of the main elements of the concept: The MFA module used to calculate demand (see Section 2.2.f); the analysis module to determine supply (see Section 2.4) as well as their linkage by assumptions regarding spatial proximity as well as documented supply notes (see Section 2.5).

2.2. Material Flow Analysis to Calculate Material Demand for Buildings

Buildings are distinguished according to domestic and non-domestic buildings.

2.2.1. Typology of Domestic Buildings

According to their form of construction, domestic buildings in Vietnam can be classified as permanent housing (all three main structural elements, i.e., supporting columns, roof and walls, are made of sturdy materials), semi-permanent housing (two out of three structural elements are made of sturdy materials), temporary housing (one of the three structural elements are sturdy) and simple housing (all three structural elements are classified as flimsy) (see Figure 3). Further, permanent domestic buildings can be subdivided as follows: (a) Tubehouses (also called street- or shophouses), the most typical form of urban dwelling; (b) detached houses (or villas), which are appearing in many new urban areas; and (c) apartment blocks, which are becoming increasingly popular [29]. In this study, we only consider domestic buildings which contain significant quantities of mineral construction materials, i.e., permanent and semi-permanent houses. Temporary and simple houses are largely built of light materials such as sheet metal, wood and bamboo.

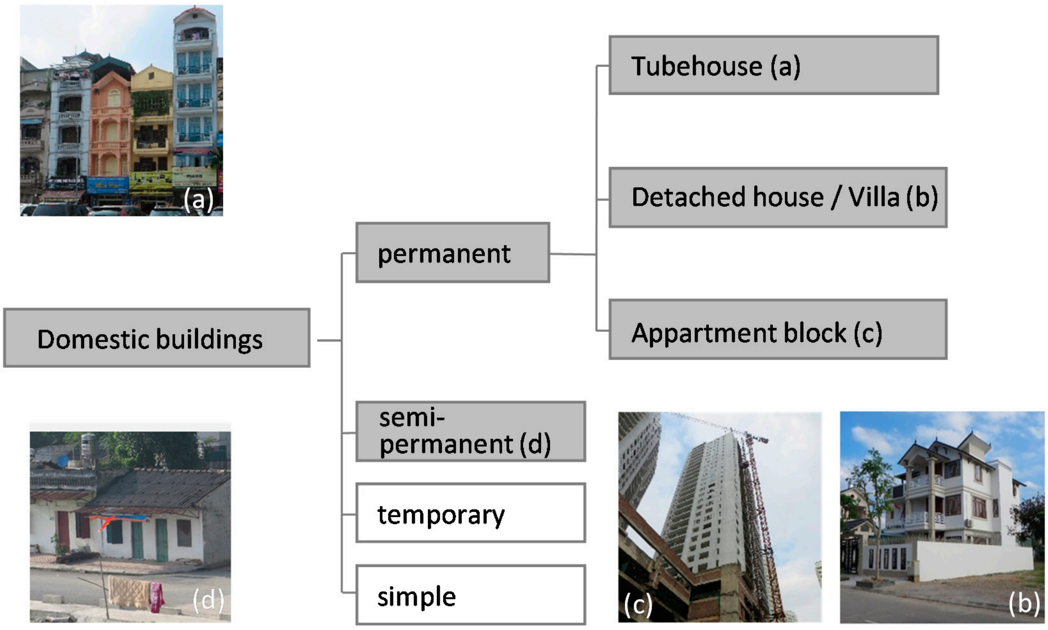

Figure 3. Classification of domestic buildings in Vietnam according to [29] (the analysed building types are marked in grey and illustrated with photographs).

2.2.2. Material Composition Indicators for Domestic Buildings

The definition of Material Composition Indicators (MCIs) for domestic buildings is based on empirical analyses of case study buildings. To this end, planning documents and expert knowledge of local architects surveyed in interviews were evaluated. The planning documents included Bills of Quantities (BoQ), i.e., previously processed mass extracts of realized building projects, as well as floor plans with Supplementary Information on the construction method of the buildings, from which the specific masses of the construction elements and buildings could be calculated using definitions of construction methods and dimensions of components indicated in the plans. To further improve the empirical basis, additional expert knowledge was also used to provide general values for the material intensity of the considered residential building types, with a focus on concrete and bricks. The experts defined specific material quantities, which they use as a basis for rough cost calculations for real projects. Two experts with a background in architecture and civil engineering were interviewed in an open setting. They hold leading positions in planning offices and enjoy several years of experience in residential construction. One of the basic requirements in their daily planning work is familiarity with standard material proportions and quantities in construction. Table 1 gives an overview of the analyzed building types as well as the method applied.

Table 1. Empirical concept for defining Material Composition Indicators (MCIs) in regard to Vietnamese domestic buildings.

Building Type	Analysis Based on *		
	Floor Plans	**Bill of Quantities**	**Expert Interviews**
Tubehouse	x (4)	x (1)	x (2)
Detached house/villa			x (2)
Apartment block	x (2)	x (1)	x (2)
Semi-permanent house	x (2)		

* Figures in brackets indicate the number of buildings analysed or the number of interviews conducted.

Based on the empirical findings indicated in Table 1 MCIs were defined for each building type by simply averaging the values assigned to the individual types (see Section 3.1)

The demand for building materials refers to products such as concrete, bricks or asphalt concrete; the supply of building materials, on the other hand, refers to raw materials such as sand, stone or clay. In order to create a link between supply and demand, MCIs are also classified in terms of raw materials (see Section 3.1). These values for the proportions of raw materials in building products are derived from the literature (see Supplementary material, Table S1). Any losses that may occur during the production of building materials are ignored.

2.2.3. Particular Measure for Domestic Building Stocks

Using data from official statistics, net floor area is taken as a measure to determine stocks of domestic buildings. We calculate the total domestic net floor area by multiplying the number of inhabitants by per capita living space. Thus we take into account both quantitative growth (population) and qualitative growth (increasing specific consumption of living space due to increasing prosperity). Official documents at provincial level provide current values for both these parameters (population Hanoi: [30]; population Hoa Binh: [31]; floor area per person Hanoi and Hoa Binh: [32]) as well as forecasts (population Hanoi: [33]; population Hoa Binh: [34]; floor area per person Hanoi: [35]; floor area per person Hoa Binh: [32]). The value calculated in this way corresponds to the total domestic net floor area. This can be broken down by building type using data from the Household Living Standard 2014 [32] (which gives corresponding percentage values for the current and future housing stock). The formula F1 is the resulting algorithm for calculating the floor area (FA) per building type of the housing stock and F2 accordingly for the entire domestic building stock.

$$FA_{\,i}\left[m^2\right] = population\ [pers.] * \ floor\ area\left[\frac{m^2}{pers.}\right] * \ building\ type_{\,i}\ [\%] \quad (1)$$

$$FA\left[m^2\right] = \sum_{i=1}^{n} FA_i \quad (2)$$

2.2.4. Material Demand for Domestic Buildings

Demand for building materials is equivalent to the quantities resulting from construction activities. The available statistics do not include data on stock changes like construction and demolition activities of domestic buildings. For this reason, the total floor space of new construction is determined indirectly: The housing stock for two consecutive years (t_1 and t_0) is calculated using data from the corresponding years. Under conditions of growth, the demand for new buildings is determined by the change in stock between times t_1 and t_0 plus the necessary replacement of demolished buildings. The total floor space of demolished buildings is assessed by means of demolition rates, based on assumptions about the average life of residential buildings. Borrowing from Huang et al. [36], we assume an average life expectancy of 30 years for residential buildings. This gives a demolition rate of 3.3 %. The formula F3 is used to determine the extent of construction in a specific period (*t0-1*) per building type (*i*) and F4 accordingly for the entire construction activities considering the housing sector.

$$construction_{\ i\ t0-1}[m] = (FA_{\ i\ t1}[m] - FA_{\ i\ t0}\left[m^2\right]) + FA_{\ i\ t0}\left[m^2\right] * demolition\ ratio\ [\%] \tag{3}$$

$$construction_{\ t0-1}[m] = \sum_{i=1}^{n} construction_{i\ t0-1} \tag{4}$$

Following the basic bottom-up principle described in Section 2.1, the resulting material flows can be calculated by applying F5, using the results of F4 and the defined MCI for domestic buildings (Section 2.2.2).

$$material\ demand_{\ t0-1}[t] = \sum_{i=1}^{n} construction_{t0-1\ i}\ [m] * MCI_{\ i}\ \left[\frac{t}{m^2}\right] \tag{5}$$

where: MCI(i) material composition indicator for building type "i" (t/m^2 net floor area), construction $t_{0\text{-}1i}$ number of constructed domestic buildings of type "i" (m^2 net floor area).

2.2.5. Material Demand for Non-Domestic Buildings

With regard to non-domestic buildings, there is a lack of basic data to enable a quantification of the building stock or its development. Similar gaps in knowledge in other countries have been pointed out by a large number of studies (an overview is provided by [37]). In many European nations, the size of the non-domestic building stock in terms of floor space is about the same as that of domestic buildings [37]. Similar estimates have been made for China's building stock with regard to the embodied materials [36]. Ortlepp et al. describe non-residential buildings in Germany's building stock as "the other half of the city" [38]. Based on these studies, we assume here that the non-domestic building stock in Vietnam is similar in size to the stock of domestic buildings. This assumption is also applied to the dynamics of the existing stock and the material compositions. The total demand for building materials for the entire building stock is thus calculated by multiplying the demand for new residential buildings by a factor of 2.

2.3. Material Flow Analysis to Calculate Material Demand for Roads

2.3.1. Typology of Roads

Two basic characteristics are used to classify the road network. The first, which refers to the connection and development function of roads, is simply the road class (RC). The second, which refers to the particular structural design of the road, is closely related to the pavement types (PTs). There are four RCs in Vietnam, namely TCVN 5729:2012 [39], TCVN 4045:2005 [40], TCVN 10380:2014 [41] and TCVN 104:2007 [42]. A distinction is made between highways, national, district, community and urban roads. These categories are further divided into subcategories. Topographical features (terrain types or TTs) are also specified to distinguish national roads. Average road widths can be determined under this system of RCs by considering national technical standards, differentiated by pavement and roadbed (Table 2).

Table 2. Road classes in Vietnam (based on TCVN 5729:2012 [39], TCVN 4045:2005 [40], TCVN 10380:2014 [41], TCVN 104:2007 [42]).

		Standard	Class/Type (Design Speed)	Average Width [m]	
				Pavement	Roadbed
Expressways		TCVN 5729:2012 [39]	Class 1 (60 km/h)	14	22
			Class 2 (80 km/h)	14	22
			Class 3 (100 km/h)	15	24.75
			Class 4 (120 km/h)	15	24.75
Highways	Plain/hilly terrain	TCVN 4045:2005 [40]	Class I (120 km/h)	22.5	32.5
			Class II (100 km/h)	15	22.5
			Class III (80 km/h)	7	12
			Class IV (60 km/h)	7	9
			Class V (40 km/h)	5.5	7.5
			Class VI (20 km/h)	3.5	6.5
National Roads	Mountainous terrain	TCVN 4045:2005 [40]	Class III (60 km/h)	6	9
			Class IV (40 km/h)	5.5	7.5
			Class V (30 km/h)	3.5	6.5
			Class VI (20 km/h)	3.5	6
Rural Roads District Road		TCVN 10380:2014 [41]	Type A	3.5	
		TCVN 4054:2005 [40]	Class IV	5.5	7.5
			Class V	3.5	6.5
			Class VI	3.5	6
Rural Roads Municipal Road		TCVN 10380:2014 [41]	Type B	3.5	5
			Type C	3	4
Urban Roads		TCVN 104:2007 [42]	Class 2: Major urban main roads	30	30
			Class 3: Main secondary urban roads	27	27
			Class 4: Side roads	12	12
			Class 5: Internal roads	7	7

Typical PTs in Vietnam are asphalt concrete, cement concrete, bitumen treated crushed stones, crushed stones and soil (see National Standards and Circulars such as [39–47]). Each PT consists of a specific number and combination of layers and is designed for an average lifespan (e.g., [42]) as shown in Table 3.

Table 3. Average lifespans of typical pavement types in Vietnam (based on TCVN 5729:2012 [39], TCVN 4045:2005 [40], TCVN 10380:2014 [41], TCVN 104:2007 [42]).

	Asphalt Concrete (High Class)	Asphalt Concrete (Low Class)	Cement Concrete	Bitumen-treat Crushed Stone	Crushed Stone	Soil
Average lifespan	≥10 years	≥10 years	≥10 years	4–7 years	3–4 years	3–4 years

2.3.2. Material Composition Indicators for Roads

MCIs for roads were determined from local norms and regulations. The information was largely obtained from Circular No. 1776/BXD-VP "Descriptions and guidance manual of construction estimating norms—Construction phase" [48] and Circular No. 1784/BXD-VP "Descriptions and guidance manual of the application of construction materials" [49].

Road pavements are mainly constructed from non-metallic minerals obtained by mining. The road embankment, serving as the foundation, consists of soil mobilized from cutting slopes/sections along the road or excavated in the near surroundings of the construction site. Thus, even though it is consumed in large quantities, this material is not considered in our calculations. The defined MCI are presented in Section 3.2.

2.3.3. Particular Measure for Roadway-Stocks and Stock Dynamics

Information on the length of the roadway network was requested from the responsible authorities (Department of Transportation) as part of interviews and made available in a written form [50,51]. Using the widths given in Table 2 for road classes "i", road areas (RA) were calculated according to F6. The breakdown of the lengths by pavement type ("j") is calculated taking into account the corresponding length proportions within the road classes (F7). Formula F8 can be used to calculate the road area of the total stock.

$$RA_i\left[m^2\right] = length_i\,[m] * width_i\,[m] \tag{6}$$

$$RA_{ij}\left[m^2\right] = RA_i\left[m^2\right] * pavement\ type_j\,[\%] \tag{7}$$

$$RA\left[m^2\right] = \sum_{i,\,j=1}^{n,\,m} RA_{ij} \tag{8}$$

The available data on the stock of roadways in Hanoi refers to the year 2016; for the province under consideration, two annual figures for roadway stocks were made available (2015 and 2016).

Two key figures are used to calculate the dynamics in the road network. The amount of new road construction was calculated using a construction rate. The quantity of roads that were renewed due to maintenance measures was determined by applying a renewal rate. The construction rate (c) was determined on the basis of the data from Hoa Binh by relating the difference between the two annual values to the total value of the baseline year. The resulting construction rate was applied to the road network in the entire study area (Hanoi and Hoa Binh). The renewal rate (r) was calculated taking into account the lifetimes of the pavement types "j" (specified in the standards (see Table 4)).

Table 4. Settlement structural indicators for the case study area.

		Population	Administrative Area (km^2)	Population Density (Inhabitants/km^2)	Per Capita Living Space (m^2/capita)
Hanoi	2015	7,390,900	3349	2207	25
	2030	9,100,000	3349	2718	32
Hoa Binh	2015	824,325	4662	177	17
	2030	1,021,331	4662	219	25

Based on these specifications, the quantity of road area to be newly built and renewed (ΔRA) in the reference years (2015 Hoa Binh, 2016 Hanoi) was determined (F9, F10).

$$\Delta RA_{ij}\left[m^2\right] = RA_{ij}\left[m^2\right] * \left(c + r_j\right) \tag{9}$$

$$\Delta RA\left[m^2\right]=\sum_{i,\ j=1}^{n,\ m}\Delta RA_{\ ij}\left[m^2\right] \tag{10}$$

2.3.4. Material Demand for Roadways

The calculation of material flows in the road network for the reference years is again based on the MFA bottom-up principle, F11.

$$material\ demand_{\ roads\ ref}[t]=\sum_{i,\ j=1}^{n,\ m}\Delta RA_{ref\ \ ij}\left[m^2\right]*MCI_{\ j}\ \left[\frac{t}{m^2}\right] \tag{11}$$

where: $\Delta RA_{ref\ \ ij}$ quantity of road area to be newly built and renewed according to road type "j" and road classes "i" in the reference year (m^2 road area), MCI(j) material composition indicator for road type "j" (t/m^2 road area).

An indirect valuation approach is used to estimate the material flow induced by road construction over the entire period under consideration (2015–2030). It is assumed that the ratios of the masses resulting from the building sector compared to those resulting from road construction will not change over this 15-year period. We define this relationship as "construction sector relationship" (CSR). In the reference years for which corresponding values could be calculated, the CSR is 0.53:0.47 for the Hanoi area and 0.90:0.10 for the province area (a detailed discussion of this topic is given in Section 4).

$$material\ demand_{\ roads\ ti}\ [t]=\frac{material\ demand_{\ buildings\ ti}[t]}{CSR_{\ reference}} \tag{12}$$

2.4. Supply Calculation

In general, the process of legislating and managing the supply of mineral construction materials and thus granting mining licenses is subject to a legislative as well as an administrative (institutional) framework. In Vietnam, the Ministry of Natural Resources and Environment (MoNRE) regulates the supply of minerals for the production of cement; all other licenses concerning the extraction of construction minerals are managed by the provincial departments (DoNREs).

In international discussion, the term "reserve" describes a mineral resource for which a valid planning permission has been granted for extraction [21]. In Vietnam, information on licensed mine reserves, reserves currently subject to a licensing procedure as well as the maximum annual mining output and the licensing period is recorded by the Register of Legal Mining Businesses, which is maintained by the DoNREs

In this study, we estimate regional supply by considering the reserves of mineral resources licensed in 2015. To forecast supply capacities from 2015 to 2030, we summed the already licensed reserves as well as those for which licenses were applied in 2015 for all registered mining companies located in Hoa Binh Province (see F13). The period of the registered licenses is between 3 and 44 years, with an average of 25 years. From this we took into account the annual quantities resulting from F13 considering the years within the period under study. In our calculations we simply assumed that no new licenses would be issued until 2030. Regarding material type, the focus was on bulk non-metallic minerals, corresponding to the construction products discussed in Chapter 2.3, namely stones (basalt and limestone), sand and clay.

$$supply\ capacity\ [t]=\sum\nolimits_{i=1}^{n} licensed\ material\ reserves_i\ [\mathrm{t}] \tag{13}$$

where licensed material $\mathrm{reserves_i}$ = material reserves in tons (t) (licensed or in the licensing process as of 2015) of mining company "i" located in Hoa Binh Province.

2.5. Case Study Area

The city of Hanoi, capital of Vietnam, located in the north of the country, and the hinterland province of Hoa Binh represent the case study area.

The population of Hanoi in 2015 was 7.4 million inhabitants, in the province 0.8 million inhabitants. Up to the year 2030 a population growth is projected in both sub-areas of the case study. Key figures for the case study are summarized in Table 4.

The boundaries of the case study area are defined by the administrative boundaries of the city of Hanoi and the province under consideration. Hoa Binh Province is one of the country's main producers of construction minerals, satisfying not only its own needs but also a significant share of the demand in Hanoi. The reserves of mineral resources within Hoa Binh Province licensed in 2015 are considered as "supply".

Based on Hoa Binh's Master Plan for Exploitation and Use of Minerals for Construction Materials, this share of the capital's needs supplied by Hoa Binh Province is in average about 35% (Resolution 76/2013/NQ-HDND, [28]); however, the figures for individual material types vary from between 0% for sand and 19% for clay to 60% for stones. The remainder of Hanoi's demand is satisfied internally as well as from other neighboring provinces, as indicated in Figure 4.

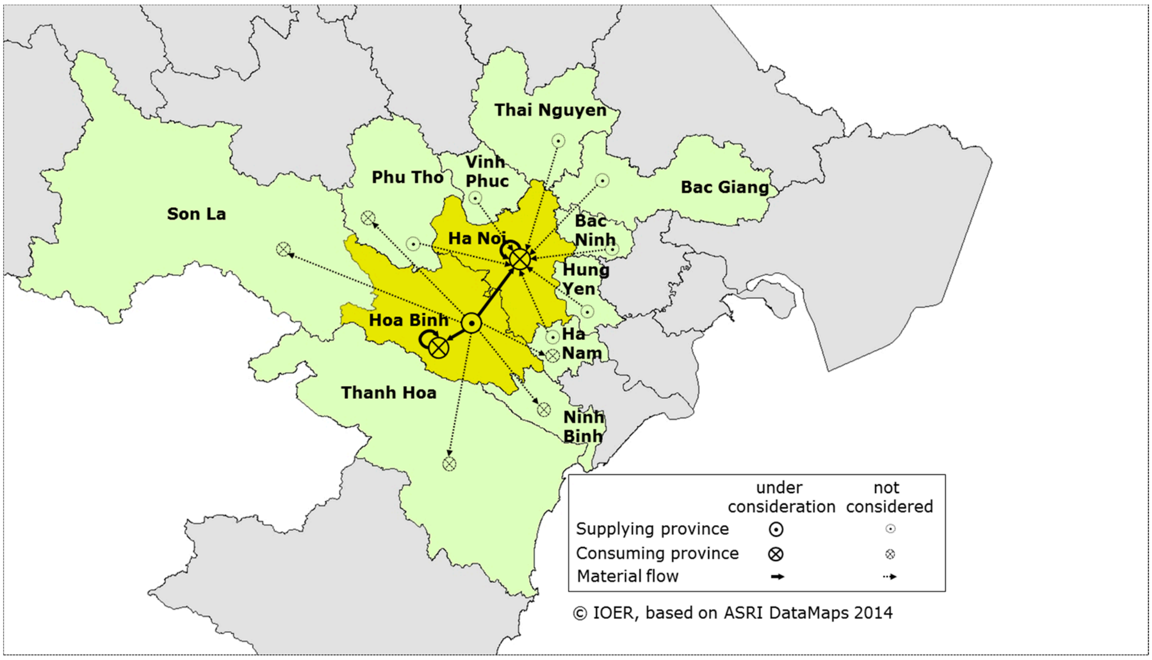

Figure 4. Spatial representation of the regional market in non-metallic construction minerals as well as supply relations within the case study area (Source: IOER Dresden, based on ESRI DataMaps2014).

Accordingly, the demand for building materials in the case study area results in part from the material requirements arising from the construction activity in the city of Hanoi. However, only those shares are taken into account whose delivery from the province Hoa Binh is planned according to [28] (see previous explanations). In addition, a further part of the demand arises from the construction activity within the province under study.

3. Results

In this section, we first present the material composition indicators (Sections 3.1 and 3.2) that we have defined using the methodological approach described in Sections 2.2 and 2.3. Subsequently, we present results of the calculation of the demand for aggregates, sand and clay in comparison with the available supply of these materials (Section 3.3).

3.1. Defined Material Composition Indicators for Buildings

Figure 5 and Table 5 show the material composition of the assessed domestic buildings, their percentage shares as well as the absolute values in relation to m^2 floor area. Table 5 also specifies the calculated raw material composition of the building types.

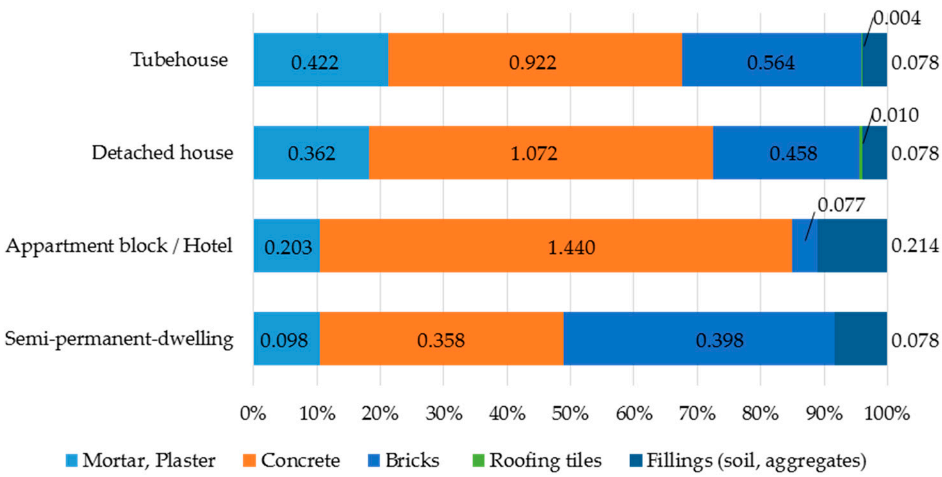

Figure 5. Material Composition Indicators (MCIs) of typical domestic buildings in Vietnam analysed by building material—percentage shares (scaling of the axis) as well as absolute values in t/m^2 floor area (numerical values in each colored segment).

Table 5. Material Composition Indicators (MCIs) of domestic building types in Vietnam classified according to building materials and raw materials.

	MCI [t/m^2 Floor Area]									
	Building Material					Raw Material				Total
	Mortar, Plaster	Concrete	Bricks	Roof tiles	Fillings (soil/aggregates)	Sand	Limestone/ Basalt	Clay	Soil/aggregates (Fillings)	
Tubehouse	0.42	0.92	0.56	0.00	0.08	0.60	0.72	0.59	0.08	1.99
Detached house	0.36	1.07	0.46	0.01	0.08	0.60	0.81	0.49	0.08	1.98
Apartment block	0.203	1.440	0.08	-	0.21	0.58	1.01	0.14	0.21	1.93
Semi-permanent houses	0.10	0.36	0.40	-	0.08	0.19	0.27	0.99	0.08	0.93

The amount of non-metallic mineral building material per m^2 floor area differs only marginally between the building types Apartment Block, Detached House and Tubehouse. Much more significant are the differences in the percentage shares of the individual building materials, especially when comparing the apartment blocks with the two other representatives of the permanent buildings. Semi-permanent buildings, however, require significantly less material per m^2 floor area and also differ significantly with regard to the material composition.

3.2. Defined Material Composition Indicators for Roads

Figure 6 and Table 6 show the MCI for roads in the corresponding format as shown in Section 3.1 for buildings.

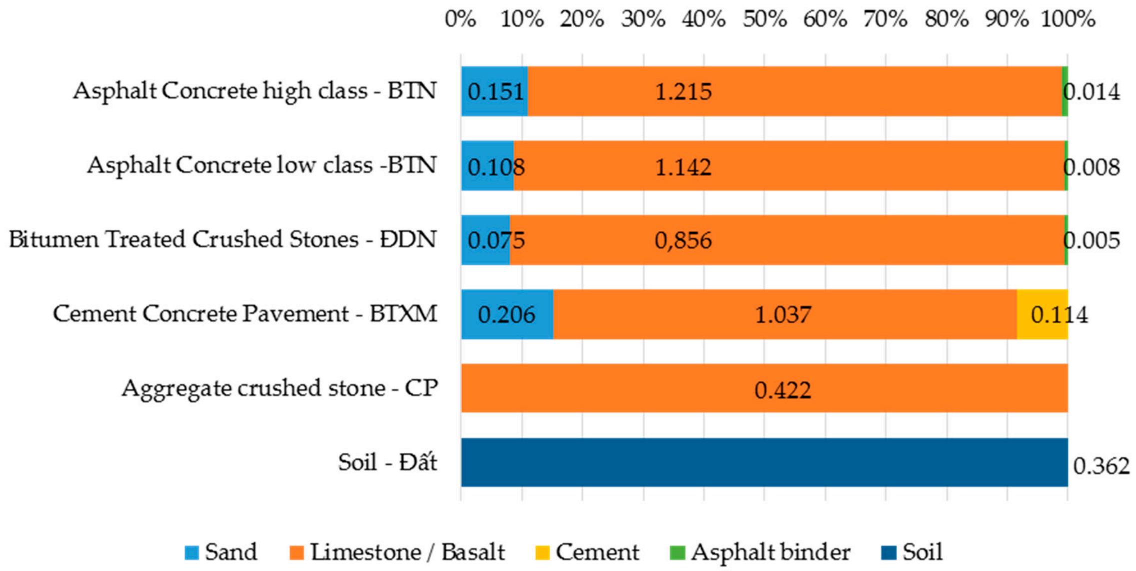

Figure 6. Percentage ratios of construction materials for typical Vietnamese road types (scaling of the axis); MCIs in t/m^2 road area (numerical values in each colored segment).

Table 6. Material Composition Indicators (MCIs) of road types in Vietnam classified according to building materials and raw materials.

	MCI [t/m^2 Road Area]									
	Building Material					**Raw Material**				**Total**
	Sand	**Aggregates (Limestone/ Basalt)**	**Cement**	**Asphalt binder**	**Soil**	**Sand**	**Aggregates (Limestone/ Basalt)**	**Clay**	**Soil, others ****	
Asphalt Concrete (hc)	0.151	1.215	-	0.014	-	0.151	1.215	-	0.014 **	1.380
Asphalt Concrete (lc)	0.108	1.142	-	0.008	-	0.108	1.142	-	0.008 **	1.258
Bitumen	0.075	0.856	-	0.005	-	0.075	0.856	-	0.005 **	0.936
Cement	0.206	1.037	0.114	-	-	0.206	1.232	0.034	-	1.357
Aggregates	-	0.422	-	-	-	-	0.422	-	-	0.422
Soil	-	-	-	-	0.362	-	-	-	0.362	0.362

**: mix of bitumen and aggregates.

The predominant building material of the analyzed road is “aggregates” (limestone/basalt). The shares of these materials are between 85% and 100%. The exception is the type “soil”, which consists of 100% soil. With regard to the total masses, the asphalt concrete and cement concrete types are of a similar order. The total mass of the road type “bitumen” is about 30% less. Significantly lower is the mass of the types “aggregates” and “soil”, whose specific mass is around 30% of the average specific mass of asphalt- and cement-concrete types.

3.3. Demand and Supply for Construction Minerals

In order to balance demand and supply of the building materials under consideration in the case study area, the annual demand for construction minerals covered by Hoa Binh province was calculated as a three-year moving average [52] and summed over the period 2015 to 2030. This demand is compared in Figure 7 with the existing supply of these materials from Hoa Binh province. The calculation of demand is based on the assumption that in average 35% of Hanoi’s demand for mineral construction materials (see Section 2.5) and Hoa Binh’s own needs are covered by the resource reserves from Hoa Binh

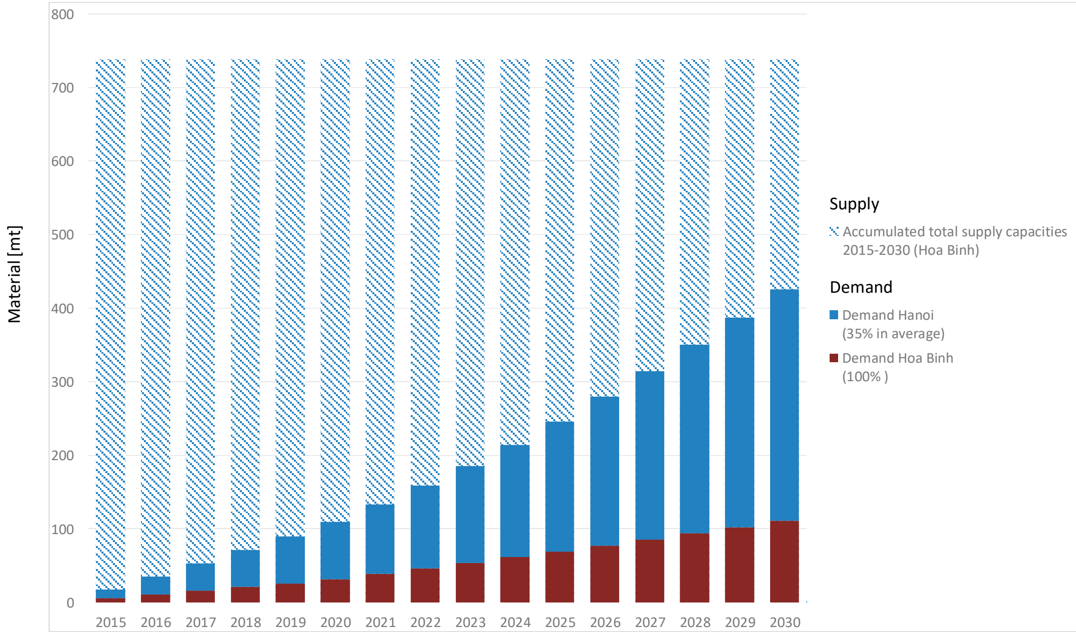

Figure 7. Accumulated supply and demand of construction mineral (aggregates, sand and clay) in Hoa Binh Province and Hanoi.

The figure shows that material supply will far exceed demand in the case study area. The calculated demand corresponds to 58% of the available supply of mineral building materials. 74% of total demand results from the demand of Hanoi, 26% from construction activity in the province.

Figure 7 makes no distinction between individual building materials, neither in terms of supply nor demand. However, the available data allow for further differentiation by material type. The Register of Legal Mining provides more detailed information on sand, limestone, basalt and clay reserves in Hoa Binh Province. With the applied bottom-up approach, the demand for these materials can be calculated individually. Furthermore, the supply relationships between Hanoi and Hoa Binh described in the Master Plan for Exploitation and Use of Minerals for Construction Materials (Resolution 76/2013/NQ-HDND) [28] (see Section 2.5) allow a differentiation between these material types. We take this up in Figures 8–10, comparing the demand and potential reserves of three mineral materials, namely aggregate (limestone, basalt), sand and clay.

Figure 8 indicates that Hoa Binh has very large reserves of limestone and basalt, which is projected to exceed accumulated demand by 2030. The calculated demand is 38% of the supply approved for mining; 77% of the quantity demanded results from the building activity of Hanoi.

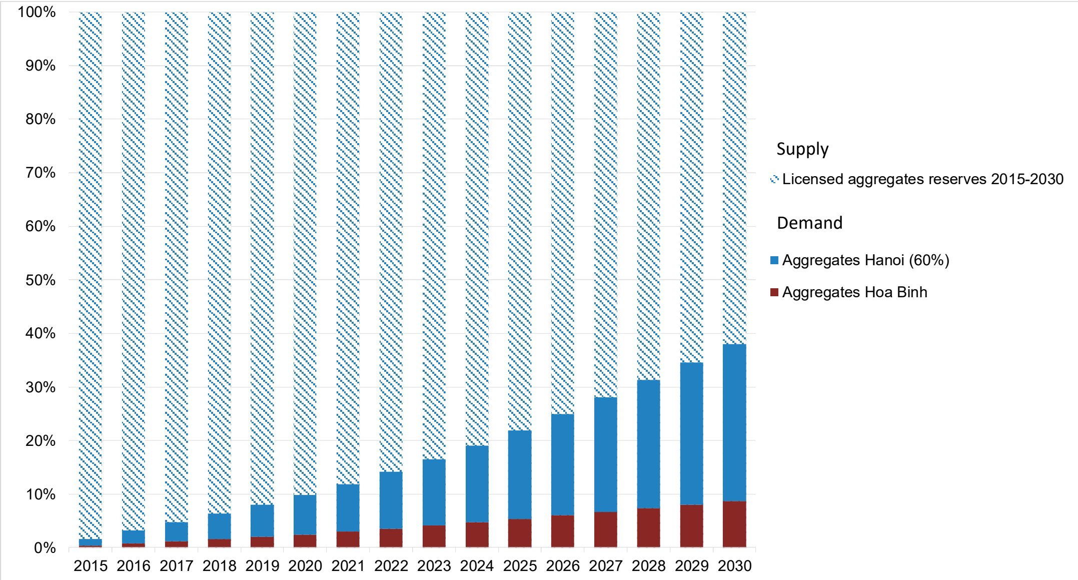

Figure 8. Accumulated demand for aggregates covered by Hoa Binh Province in relation to local mineral reserves.

A completely different pattern can be observed in regard to the supply and demand of natural river sand: The sand reserves of Hoa Binh may be outstripped by the demand from the construction sector within a period of 9 years (Figure 9), although the entire demand for sand results from the province's own consumption.

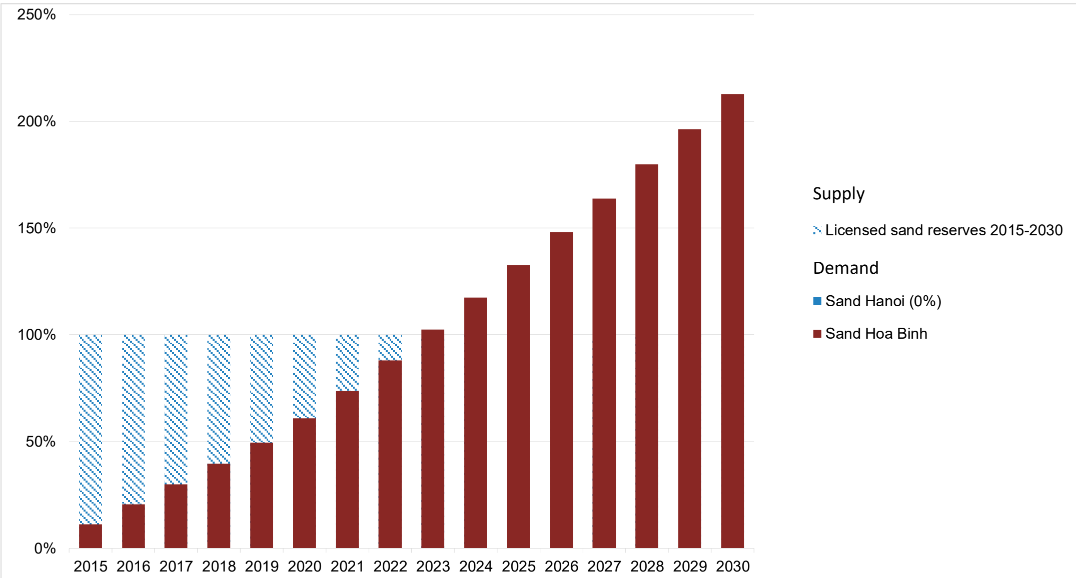

Figure 9. Accumulated demand for sand covered by Hoa Binh Province in relation to local reserves.

Even more extreme is the lack of coverage of the existing demand for clay by the licensed supply of the related material (Figure 10). The available resources are only sufficient to meet the demand resulting from the province's own needs for half the period under consideration. This period is cut to 4 to 5 years if the demand from Hanoi is also taken into account.

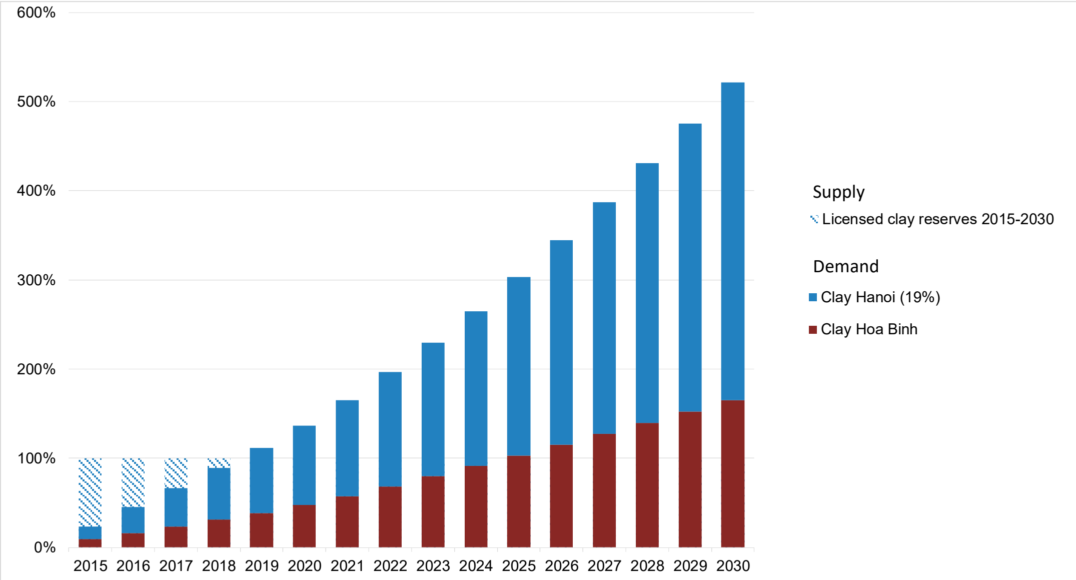

Figure 10. Accumulated demand for clay covered by Hoa Binh Province in relation to local reserves.

Table 7 below provides an overview of the consumption of building materials in the two sub-areas of the case study as well as the available reserves to cover the demand resulting from this consumption.

Table 7. Demand for construction minerals covered by Hoa Binh Province in 2015 and 2030 (accumulated) and Hoa Binh's reserves in absolute values.

	Reserves in 2015 [mt]	Consumption in 2015 [mt]		Accumulated Demand 2015–2030 [mt]	
	Already licensed or in the licensing process	Hanoi (100%)	Hoa Binh (100%)	Hanoi (100%)	Hoa Binh (100%)
Clay	12.13	9.88	0.90	245.54	21.25
Sand	11.14	10.54	1.02	262.13	26.46
Aggregates	715.26	15.75	3.23	391.58	65.54

4. Discussion

4.1. Uncertainties and Plausibility

MFA is an efficient tool to analyse materials and their flows within the built environment. However, coefficient-based MFA models are structurally fraught with uncertainty. Laner et al. distinguish various sources of uncertainty such as statistical disparities, variability in parameters over space and time, unpredictability, subjective judgments, scientific disagreements, linguistic imprecision or approximations due to model simplifications and assumptions [53]. Ortlepp et al. have suggested distinguishing between parameter uncertainties due to input data and modeling uncertainties related to outcomes [20]. In this study, parameter uncertainties refer, in particular, to the generation of MCIs (empirical database, the variable weighting of parameters over space and time), neglected material losses, as well as the partially incomplete statistical data.

The definition of MCIs for domestic buildings is based on a mix of different empirical concepts (see Section 2.2.2). Similar combination approaches can certainly be found in the literature (e.g., [54]). Overall, these are aimed at improving an empirical database that is generally weak by using different sources. This is accompanied by uncertainties, which cannot be quantified in more detail here. It should be noted, however, that there is a great variety of approaches in literature, in particular the range of different types, the type of differentiation according to material groups and the choice of a reference variable to which the material indicators refer [55]. This makes it difficult to check plausibility by comparison with corresponding key figures from other studies. A present study provided by Schiller et al., which compares Japanese and German buildings, concludes that cultural aspects and local building traditions have a considerable influence, especially in the case of single-family houses [55]. In the case of multi-family houses, on the other hand, geophysical conditions such as the properties of the subsoil, earthquake risks and similar factors dominate the characteristics of the construction methods and thus also the material composition. The investigation of such influencing factors was not the subject of this study. Thus, the only option left for plausibility checks is the comparison of value ranges. In the case of permanent buildings, the key figures determined in this study for buildings are just below 2 metric tons/m^2 living space. The cited comparative study shows values between 1.4 (Germany) and 2.2 (Japan) metric tons for comparable buildings. While the values in this study refer to floor area in the sense of living space, the quoted values from the above-mentioned study refer to net floor area, which is around 10% larger than living space [55]. If the reference scale were adjusted accordingly, the values from Schiller et al. would increase by approx. 10%. The values used here would consequently be in the middle of this value range. This leads to the conclusion that the values are at least not implausible. To check the plausibility of MCIs for roads, a study on material investigations in the Vietnamese road network can be consulted [56]. The specific masses of comparable categories given there are about a quarter higher than those determined in this study. The underlying methodology of the two compared studies is the same, but different standards are used to define the MCIs. It can therefore be assumed that the values presented here are rather at the lower end of a range.

Model uncertainties encompass all assumptions and simplifications that distinguish the model from reality. Here, these include assumptions about material requirements for non-domestic buildings, their useful lifetime and supply relationships. The assumptions on the renewal intervals of roads and buildings have a significant influence on the annual material flows. For roads, these are assumed in this study to be half as long as the values given in [56]. However, it should be noted that the present study refers to local (Vietnamese) standards in this respect, while the corresponding parameters used in [56] are taken from the European context. With regard to building lifetimes, no values with direct reference to Vietnam are available, but the study provided by Huang and colleagues [36], from which corresponding values were taken, does at least refer to the region and thus to a similar geographical and cultural context.

While the analysis model for residential buildings could be closely linked to the dynamic bottom-up MFA method, this was not possible for nondomestic buildings and for roads due to unidentified model parameters. Instead, general assumptions were applied (see Figure 2, Section 2.1). Again, a plausibility check can only be carried out with reference to the results of other studies. The assumption regarding non-domestic buildings (size material stock in non-domestic buildings = size material stock in domestic buildings) is already supported by corresponding references in Section 2.2.5. In the case of roads, it was possible to describe initial stock levels and stock change parameters at least for part of the case study area on the basis of available data. Due to insufficiently available data for different periods of time, however, here too we used generalized relations of the building material masses from different sub-sectors of the built environment—in this case relations of the masses from the building sector and the road sector, defined as "construction sector relationship" (CSR) (Section 2.3.4). In principle, it can be observed that the proportion of masses resulting from roads is significantly lower in dense urban areas than in moderate dense regions. For example, the share of material flows induced by the road network of Chinese cities (Beijing, Tianjin and Shanghai) is 3% compared to 97% induced by buildings [36]. A study related to the built environment of Japan allocates 38% of total material flows to roads [57]. In Germany, 47% of material flows in the construction industry were attributed to the road construction sector [18]. It is important to note that Germany is much less densely populated than Japan. In the light of these comparative values, the CSR identified in this study and applied in the model are generally within plausible ranges.

To some extent, the calculated total masses also allow a plausibility check against available benchmarks if they are standardized accordingly. Related to the year 2015, the consumption of mineral building materials in Hanoi as determined in this study adds up to 4.9 metric tons per capita. In Hoa Binh, the corresponding value is 6.2 metric tons per capita. According to the United Nations, the global average material footprint in 2017 exceeded 12 metric tons per capita [58]. This includes non-metallic mineral materials as well as other materials, namely biomass, fossil fuels, metal ores and others. In Germany, the share of minerals in the total social material consumption in 2008 was about 40%, which corresponds to a value of about 6.5 metric tons per capita [59]. Schiller and colleagues determined for Germany a value of approximately 4 metric tons per capita annual consumption of mineral building materials in 2010 [18]. The studies mentioned above used different methods. While the above cited United Nations Study ([58]) as well the mentioned study related to the German context [59] both follow an economy-wide MFA approach (ewMFA) (see [60]), the value taken from Schiller and colleagues ([18]) is based on bottom-up analyses, as used in this study. For methodological reasons, bottom-up approaches tend to underestimate the amount of material flows, as not all construction measures are necessarily considered [18]. Against this background, the values calculated in this study appear comparatively high. Somewhat surprising is also the high value for Hoa Binh province. This obviously reflects the high proportion of contributions from road construction, which is also reflected indirectly in local planning documents. The Socio-Economic Development Strategy (SEDS) defines the long-term goals to be attained within a 10-year period, serving as a basis for the formulation of sectoral and local development plans. The SEDS identifies new infrastructure as one of the three essential areas of development [61]. The Provincial Master Plans on Socio-economic Development for Hanoi City (Decision 1081/QD-TTg, [62]) and Hoa Binh Province (Decision 917/QD-TTg, [63]) define explicit midterm objectives in Hoa Binh Province such as to "build a complete and modern infrastructure system (upgrade national highway 6, build Hoa Lac-Hoa Bihn city road, several new roads and bridges)". Given this background information, the ongoing extraordinary construction boom in Vietnam [14] and the fact that the case study region Greater Hanoi is the second largest urban agglomeration in Vietnam [64], the figures do not appear implausible.

4.2. Potentials of the Approach

4.2.1. Securing Raw Materials

The management of mining is a multi-actor and multi-level task. According to Östensson [65], the key stakeholders in this field of activity are governments at national and regional level, the mining industry, local communities, and non-governmental organizations (NGOs). Governments must find a balance between, on the one hand, protecting the natural environment and conserving non-renewable finite resources, and, on the other, promoting economic growth. A regulatory system is required to ensure this balance, supported by an explicit and data-based description of the current situation and future scenarios. That was the aim of this study, namely to describe and compare (quantitatively and qualitatively) the demand and supply of construction minerals in Hanoi and the hinterland province Hoa Binh and to identify possible supply bottlenecks. The generated results are addressed to all parties involved in mining management, regional and urban planning as well as raw material security planning for the construction industry.

The results were compared with existing planning documents and discussed with mining companies and planning authorities. The very short-term planning horizon foreseen in the Master Plan for Exploitation and Use of Minerals for Construction Materials of Hoa Binh Province (Resolution 76/2013/NQ-HDND [28]) of only 5 years is highly problematic; a long-term licensing strategy would boost the aim of sustainability. While the demand for minerals is projected to grow, reflecting the rising consumption of previous years, statistics issued by the Department of Construction in Hoa Binh [28] show that the consumption of construction materials does not obey a general rule and is highly dependent on the level of investment and the health of the real estate market. The MFA approach presented in this study is ideally suited to simulating longer-term demand developments based not only on trend forecasts but on detailed estimates of material stocks and flows derived from population figures and data supplied by the construction industry and urban planners as well as strategic development targets.

4.2.2. Support Sustainable Material Substitution Strategies

The described MFA approach also enables the quantitative and qualitative description of concrete solution-oriented scenarios such as the substitution potential of construction minerals in buildings and infrastructures (e.g., to substitute natural sand by artificial sand [66]) and the respective effects on the supplying hinterland. This is only possible if the generated data is sufficiently differentiated, transparent and empirically based. In any discussion on material substitution, it is vital that material demand and supply be broken down by material type. Here it should be pointed out that while our results can provide a general orientation when drawing up strategies for the mining industry, they need to be further elaborated for concrete planning tasks. The general and comprehensive nature of the presented results can help to identify interdisciplinary linkages and thus underpin integrated discussions of the strategic direction to be adopted.

5. Conclusions

With the presented research, an approach of a regional material flow analysis was presented for the first time which quantifies and compares the supply and demand of mineral building materials within an urban region. In general, the bottom-up MFA method offers a suitable approach for this purpose. However, the partly very weak data basis proves to be problematic, which hampers a robust description of the building and infrastructure stock. With suitable assumptions, backed up by the literature, it is possible to close gaps, make general trend statements possible, and achieve results that stand up to comparison with benchmarks from the literature.

It is obvious from the results that scarcity of raw materials can, by nature, take very different forms with regard to different categories of materials in a specific spatial context. The identification and quantification of these interrelationships within specific regions facilitates the design of comprehensive strategies for securing raw materials. However, this also supports an extended assessment of the resource efficiency of urbanization, taking into account aspects of the availability of raw materials. It becomes clear that resource efficiency and sustainability can only be achieved if the hinterland is adequately considered. This offers new perspectives for the search for appropriate strategies of material substitution and their specification. The viewpoint taken here also emphasizes the importance of cross-sectoral planning. What is needed is a strong integration of settlement planning in urban areas with resource planning and affected land use planning in the hinterland.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/11/4358/s1, Table S1: Raw material content of construction materials.

Author Contributions: All authors were involved in the design of the paper. G.S. created the project concept for the MAREX subproject on Material Flow Analysis (MFA). T.B. calculated the material flows for the supply and demand of building materials. Both of them coordinated and conducted the data collection, designed the model and wrote the paper. A.T.V.P. supported the collection of data from Vietnamese sources, contributed to the methodological discussion and reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

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References

1. United Nations Department of Economic and Social Affairs/Population Division. World Urbanization Prospects: The 2014 Revision, Highlights. 2014. Available online: https://read.un-ilibrary.org/human-settlements-and-urban-issues/world-urbanization-prospects_527e5125-en#page1 (accessed on 6 March 2020).
2. Le, H.T.; Booth, A.L. *Inequality in Vietnamese Urban-Rural Living Standards, 1993–2006*; Discussion Paper No. 4987; Forschungsinstitut zur Zukunft der Arbeit: Bonn, Germany, 2010; Available online: http://repec.iza.org/dp4987.pdf (accessed on 18 October 2019).
3. Augiseau, V.; Barles, S. Studying construction materials flows and stock: A review. *Resour. Conserv. Recycl.* **2017**, *123*, 153–164. [CrossRef]
4. Fritsche, U.R.; Eppler, U.; Iriarte, L.; Laaks, S. Resource-Efficient Land Use—Towards a Global Sustainable Land Use Standard (GLOBALANDS). 2015. Available online: http://www.umweltbundesamt.de/publikationen/resource-efficient-land-use-towards-a-globa (accessed on 18 October 2019).
5. Schiller, G.; Bimesmeier, T.; Tran, H. Bridging Urban Rural Dichotomy Following Construction Material Flows of Urbanization. Proceedings. 2018. Available online: http://regionalscience.org/images/PDF/Proceedings_RSAICongress2018.pdf (accessed on 18 October 2019).
6. Krausmann, F.; Wiedenhofer, D.; Lauk, C.; Haas, W.; Tanikawa, H.; Fishman, T.; Miatto, A.; Schandl, H.; Haberl, H. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 1880–1885. [CrossRef] [PubMed]
7. Wilburn, D.R.; Goonan, T.G. Aggregates from natural and recycled sources—Economic assessments for construction applications: U.S. Geological Survey Circular 1176. 1998. Available online: http://greenwood.cr.usgs.gov/pub/circulars/c1176/c1176.html (accessed on 8 August 2018).
8. Pacheco-Torgal, F.; Cabeza, L.; Labrincha, J.; de Magalhães, A. *Eco Efficient Construction and Building Materials*; Woodhead Publishing: Oxford, UK, 2013; Available online: https://www.elsevier.com/books/eco-efficient-construction-and-building-materials/pacheco-torgal/978-0-85709-767-5 (accessed on 18 October 2019).
9. Schiller, G.; Gruhler, K.; Ortlepp, R. Continuous Material Flow Analysis Approach for Bulk Nonmetallic Mineral Construction materials Applied to the German Building Sector. *J. Ind. Ecol.* **2017**, *21*, 673–688. [CrossRef]
10. Tuoi Tre News. Vietnam Forecast to Run Out of Construction Sand by 2020. 14:23 GMT+7. 3 August 2017. Available online: https://tuoitrenews.vn/news/society/20170803/vietnam-forecast-to-run-out-of-construction-sand-by-2020/40865.html (accessed on 18 October 2019).
11. Sing MC, P.; Love, P.; Tam, C. Review and exploration of river sand substitutes for concrete production in Asian countries. *CEBM* **2012**, 115–117. [CrossRef]
12. Ortlepp, R.; Schiller, G.; Sebesvari, Z. Building Material Substitutes Contra Topsoil Harvesting—Technical Considerations with Focus on Developing Countries. 2015. Available online: http://sasbe2015.com/wp-content/uploads/2015/09/SASBE201574_OrtleppSchillerSebesvari.pdf (accessed on 10 March 2020).
13. Kittipongvises, S. Assessment of Environmental Impacts of Limestone Quarrying Operations in Thailand. *Environ. Clim. Technol.* **2017**, *20*, 67–83. [CrossRef]
14. Schneider, P.; Oswald, K.-D.; Riedel, W.; Meyer, A.; Schiller, G.; Bimesmeier, T.; Viet AP, T.; Nguyen, K.L. Engineering Perspectives and Environmental Life Cycle Optimization to Enhance Aggregate Mining in Vietnam. *Sustainability* **2018**, *10*, 525. [CrossRef]
15. Binstock, M.; Carter-Whitney, M. Aggregate Extraction in Ontario: A Strategy for the Future. Executive Summary. Canadian Institute for Environmental Law and Policy [WWW Document]. 2011. Available online: http://cielap.org/pdf/AggregatesStrategyExecSumm.pdf (accessed on 18 October 2019).
16. Müller, E.; Hilty, L.M.; Widmer, R.; Schluep, M.; Faulstich, M. Modeling metal stocks and flows: A review of dynamic material analysis methods. *Environ. Sci. Technol.* **2014**, *48*, 2102–2113. [CrossRef]
17. Kennedy, C.A. Industrial Ecology and Cities. In *Taking Stock of Industrial Ecology*; Clift, R., Druckman, A., Eds.; Springer International Publishing: Cham, Switzerland, 2016; pp. 69–86. Available online: https://link.springer.com/chapter/10.1007/978-3-319-20571-7_4 (accessed on 10 March 2020).
18. Schiller, G.; Müller, F.; Ortlepp, R. Mapping the anthropogenic stock in Germany: Metabolic evidence for a circular economy. *Resour. Conserv. Recycl.* **2017**, *123*, 93–107. [CrossRef]

19. Müller, D.B. Stock dynamics for forecasting material flows: Case study for housing in The Netherlands. *Ecol. Econ.* **2006**, *59*, 142–156. [CrossRef]
20. Ortlepp, R.; Gruhler, K.; Schiller, G. Materials in Germany's domestic building stock: Calculation model and uncertainties. *Build. Res. Inf.* **2018**, *46*, 164–178. [CrossRef]
21. Langer, W.H. An overview of aggregate resources in the United States. In *Industrial Minerals and Extractive Industry Geology*; Scott, P.W., Bristow, C.M., Eds.; Geological Society London: London, UK, 2010; Available online: http://www.gbv.de/dms/goettingen/354889346.pdf (accessed on 10 March 2020).
22. Wilbrun, D.R.; Goonan, G.T. Aggregates from Natural Recycled Sources. Economic Assessment for Construction Applications—A Materials Flow Analysis. Denver: U.S. Department of the Interior. U.S. Geological Survey Circular no. 1176. Available online: http://pubs.usgs.gov/circ/1998/c1176/c1176.html (accessed on 25 April 2016).
23. Miliutenko, S. Aggregate provision and sustainability issues in selected European cities around the Baltic Sea. Master's Thesis, KTH Royal Institute of Technology, Stokholm, Sweden, 2009.
24. Chisholm, G.G. *Handbook of Commercial Geography*; Longman, Green & Co.: London, UK, 1889.
25. Suchet, A. Le concept d'arrière-pays en géographie: Une promenade dans la littérature. *ERÍA* **2017**, *37*, 125–130. [CrossRef]
26. Britannica, E. Hinterland. Available online: https://www.britannica.com/science/hinterland (accessed on 10 March 2020).
27. Kissinger, M.; Haim, A. Urban hinterlands - The case of an Israeli town ecological footprint. *Environ. Dev. Sustain.* **2008**, *10*, 391–405. [CrossRef]
28. Department of Construction Hoa Binh. *Resolution 76/2013/NQ-HDND: Master Plan for Exploitation and Use of Minerals for Construction Materials of Hoa Binh Province: Stones and Sand for Construction Materials, CLAY for Bricks in Hoa Binh Province, Period 2014–2019, with a Vision to 2024*; Department of Construction: Hoa Binh, Vietnam, 2013.
29. UN-Habitat 2013. Vietnam Housing Sector Profile. 2013. Available online: https://unhabitat.org/sites/default/files/download-manager-files/HousingEDIT-ENG%20%28PDF%29_low-Copy.pdf (accessed on 10 March 2020).
30. Hanoi Statistical Office. *Hanoi Statistical Yearbook 2015*; Vietnam Statistical Publishing House: Hanoi, Vietnam, 2016.
31. Hoa Binh Statistical Office. *Hoa Binh Statistical Yearbook 2015*; Vietnam Statistical Publishing House: Hanoi, Vietnam, 2016.
32. General Statistical Office Viet Nam. *Result of the Vietnam Household Living Standards Survey 2014*; Statistical Publishing House: Hanoi, Vietnam, 2016.
33. Ministry of Construction. *Decision No. 1259/QD-TTg: Approving the General Planning on Construction of Hanoi Capital up to 2030, with a Vision toward 2050*; Ministry of Construction: Hanoi, Vietnam, 2011.
34. Department of Construction Hoa Binh. *The Report of Housing Development Program in Hoa Binh Province till 2020 and Vision to 2030*; Department of Construction: Hoa Binh, Vietnam, 2014.
35. Department of Construction Hanoi. *Decision 996/QD-TTg Approval of Housing Development Programme in Hanoi for the 2012–2020 Period with the Orientation by the Year 2030*; Department of Construction: Hanoi, Vietnam, 2014.
36. Huang, C.; Han, J.; Chen, W.Q. Changing patterns and determinants of infrastructures' material stocks in Chinese cities. *Resour. Conserv. Recycl.* **2016**, *123*, 47–53. [CrossRef]
37. Ortlepp, R.; Gruhler, K.; Schiller, G. Material stocks in Germany's non-domestic buildings: A new quantification method. *Build. Res. Inf.* **2016**, *44*, 840–862. [CrossRef]
38. Ortlepp, R.; Gruhler, K.; Schiller, G.; Deilmann, C. The other 'half of the city'—Analysis of non-residential building stock and its material. In Proceedings of the Smart and Sustainable Built Environment (SASBE) Conference 2015, Pretoria, South Africa, 9–11 December 2015; Gibberd, J., Conradie, D.C.U., Eds.; University of Pretoria: Pretoria, South Africa, 2015; pp. 271–280. Available online: http://sasbe2015.com/wp-content/uploads/2015/09/SASBE201573_OrtleppGruhlerSchillerDeilmann.pdf (accessed on 10 March 2020).
39. Ministry of Transport and Communications. *TCVN 5729:2012: Expressway—Specifications for Design*; Ministry of Transport and Communications: Hanoi, Vietnam, 2012.
40. Ministry of Transport and Communications. *TCVN 4054:2005: Highway—Specifications for Design*; Ministry of Transport and Communications: Hanoi, Vietnam, 2005.

41. Ministry of Transport and Communications. *TCVN 10380:2014: Rural—Specifications for Design*; Ministry of Transport and Communications: Hanoi, Vietnam, 2014.
42. Ministry of Transport and Communications. *TCVN 104:2007: Urban Road—Specifications for Design*; Ministry of Transport and Communications: Hanoi, Vietnam, 2007.
43. Ministry of Transport and Communications. *TCVN 8857: 2011: Natural Aggregate for Road Pavement Layers Specification for Material, Construction and Acceptance*; Ministry of Transport and Communications: Hanoi, Vietnam, 2011.
44. Ministry of Transport and Communications. *TCVN 8858: 2011: Cement Treated Aggregate Bases for Road Pavement—Specification for Construction and Acceptance*; Ministry of Transport and Communications: Hanoi, Vietnam, 2011.
45. Ministry of Transport and Communications. *TCVN 8859: 2011: Graded Aggregate Bases and Subbases Pavement—Specification for Construction and Acceptance*; Ministry of Transport and Communications: Hanoi, Vietnam, 2011.
46. Ministry of Transport and Communications. *TCVN 9504: 2012: Specification for Construction and Acceptance of Water Bound Macadam Layer*; Ministry of Transport and Communications: Hanoi, Vietnam, 2012.
47. Ministry of Transport and Communications. *Circular No. 12/2013/TT-BGTVT: Circular of Prescribing the Use of Cement Concrete Road Surface Structure in Construction of Traffic Works*; Ministry of Transport and Communications: Hanoi, Vietnam, 2013.
48. Ministry of Construction. *Circular No. 1776/BXD-VP: Descriptions and Guidance Manual of Construction Estimating Norms—Construction Phase*; Ministry of Construction: Hanoi, Vietnam, 2007.
49. Ministry of Construction. *Circular No. 1784/BXD-VP: Descriptions and Guidance Manual of the Application of Construction Materials*; Ministry of Construction: Hanoi, Vietnam, 2007.
50. Department of Transportation Hanoi. Cung Cấp Nôi Dung Làm Viêc—Với Doàn Chuyên Gia Thực Hiên Án MAREX [Content Delivery–For the MAREX Project Experts Team]. 18 November 2016.
51. Department of Transportation Hoa Binh. Quyết Đinh-Phê Duy Êt Danh Muc Ha Tầng Giao Thông Do Thàn Phố Quản Lý Sau Đầu Tư Theo Đinh Tai Quyết Đinh Số 14/2016 [Decision—Approval of the list of transport infrastructure managed by the City in accordance with Decision No 14/2016]. 20 December 2016.
52. Miatto, A.; Schandl, H.; Wiedenhofer, D.; Krausmann, F.; Tanikawa, H. Modeling material flows and stocks of the road network in the United States 1905–2015. *Resour. Conserv. Recycl.* **2017**, *127*, 168–178. [CrossRef]
53. Laner, D.; Rechberger, H.; Astrup, T. Systematic evaluation of uncertainty in material flow analysis. *J. Ind. Ecol.* **2014**, *18*, 859–870. [CrossRef]
54. Kleemann, F.; Lederer, J.; Aschenbrenner, P.; Rechberger, H.; Fellner, J. A method for determining buildings'material composition prior to demolition. *Build. Res. Inf.* **2016**, *44*, 368–380. [CrossRef]
55. Schiller, G.; Miatto, A.; Gruhler, K.; Ortlepp, R.; Deilmann, C.; Tanikawa, H. Transferability of material composition indicators for residential buildings: A conceptual approach based on a German-Japanese comparison. *J. Ind. Ecol.* **2019**, *23*, 796–807. [CrossRef]
56. Nguyen, T.C.; Fishman, T.; Miatto, A.; Tanikawa, H. Estimating the Material Stock of Roads, The Vietnamese Case Study. *J. Ind. Ecol.* **2019**, *23*, 663–673. [CrossRef]
57. Tanikawa, H.; Fishman, T.; Okuoka, K.; Sugimoto, K. The weight of society over time and space: A comprehensive account of the construction material stock of Japan, The construction material stock of Japan. *J. Ind. Ecol.* **2015**, *19*, 778–791. [CrossRef]
58. United Nations; Department of Economic and Social Affairs; Statistics Division. SDG Goals, 12 Responsible Consumption and Production, Ensure Sustainable Consumption and Production Patterns. 2020. Available online: https://unstats.un.org/sdgs/report/2019/goal-12/ (accessed on 18 October 2019).
59. Dittrich, M.; Giljum, S.; Lutter, S.; Polzin, C. Update of national and international resource use indicators, UBA, Texte, August 2013. Available online: https://www.umweltbundesamt.de/publikationen/update-of-national-international-resource-use (accessed on 10 March 2020).
60. Eurostat. *Economy-wide Material Flow Accounts (EW-MFA). Compilation Guide*; Eurostat: Luxembourg, 2013. Available online: ec.europa.eu/eurostat/documents/1798247/6191533/2013-EW-MFA-Guide-10Sep2013,pdf/54087dfb-1fb0-40f2-b1e4-64ed22ae3f4c (accessed on 18 October 2019).
61. World Bank. Vietnam Urbanization Review. Technical Assistance Report. 2011. Available online: http://www.citiesalliance.org/sites/citiesalliance.org/files/CAFiles/Projects/Final_669160ESW0P1130Review000Full0report.pdf (accessed on 8 August 2018).

62. Prime Minister of Vietnam. *Decision No. 1081/QD-TTg of Juiy 6, 2011: Approving the Master Plan on Socio-Economic Development of Hanoi City through 2020, with Orientations toward 2030*; Prime Minister of Vietnam: Hanoi, Vietnam, 2011.
63. Prime Minister of Vietnam. *Decision No. 917/QD-TTg of June 11, 2013, Approving the Master Plan on Socio-Economic Development of Hoa Binh Province through 2020*; Prime Minister of Vietnam: Hanoi, Vietnam, 2013.
64. Müller, B.; Wirth, P.; Schiller, G.; Bimesmeier, T.; Vu, A.M.; Albrecht, J.; Thinh, N.X.; Ebrahimi-Salari, H.; Schiappacasse, P.; Oswald, K.-D.; et al. Management of Mineral Resource Extraction in Hoa Binh Province, Vietnam. Seven Recommendations for Responsible Construction Aggregates Mining and Contributions to Sustainable Urban and Regional Development, MAREX Publication Series 1. 2019. Available online: http://www.marex-project.de/publications/final/MAREX_Issue1_WEB.pdf (accessed on 10 March 2020).
65. Östensson, O. Players in the Mineral Industry. In *International and Comparative Mineral Law and Policy: Trends and Prospects*; Bastida, E., Waelde, T.W., War-den-Fernández, J., Eds.; Kluwer Law International: The Hague, The Netherlands, 2005; pp. 429–449.
66. Joel, M. Use of Crushed Granite Fine as Replacement to River Sand in Concrete Production; 2010; Volume 9. Available online: http://lejpt.academicdirect.org/A17/085_096.pdf (accessed on 20 February 2020).