Leibniz Institute of
Ecological Urban and
Regional Development

# Regional material flow analysis

A concept for balancing supply and demand of construction minerals for regions using the example of Hanoi and the hinterland province Hoa Binh

MAREX Publication Series – Issue 5

## IMPRINT

**Regional material flow analysis –**
A concept for balancing supply and demand of construction minerals for regions using the example of Hanoi and the hinterland province Hoa Binh

Results of the project MAREX: Management of Mineral Resource Extraction in Hoa Binh Province – a Contribution to Sustainable Development in Vietnam (2015-2018)

Supported by BMBF, Grant Code FKZ 033R122A

Issue 5

Internet: www.marex-project.de



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Editorial deadline August 2018


ISBN 978-3-933053-44-2

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# 1 Introduction

**Urbanization and construction minerals**

Urbanization is a global and ongoing trend. In 2007, for the first time in history, the global urban population exceeded the global rural population and continuously increasing urbanization rates can be observed worldwide. It is even expected that roughly the reverse of the global rural-urban population distribution of the mid-twentieth century will be reached by 2050. In particular, Asian and African countries with low levels of prosperity are marked by high urbanization dynamics [67]. In Vietnam, urban areas contribute around 70-75% of national GDP annually. For this reason, promoting and supporting urbanization is the major goal of the Vietnamese Central Government. In this context, Coulthart et al. (2006) [3] state that "striving for higher classification standards has become a major preoccupation of local government authorities as urban areas of higher classes receive greater recognition and shares of financial resources" [70]. With increasing urbanization rates and increasing prosperity, the demand for construction materials is also growing. In Vietnam, for example, per capita consumption of mineral building materials in 2010 was already over 80% of the level in Germany, although the degree of urbanization was only around 30%, compared with almost 75% in Germany [72].

The link between urbanization and demand for construction materials is repeatedly noted in the literature (e.g. Cramer 2017; Fritsche et al. 2015; Schiller et al. 2018) [4, 13, 58]. Based on a worldwide survey provided by WU & Dittrich 2014 [72], construction materials contribute about one third of all domestic material demands. Of all materials in long lasting products, construction materials account for about 90% of the entire anthropogenic material stock. Within this material group, the most significant materials are non-metallic minerals such as stones, sand and clay, accounting for about 94% (Schiller et al. 2017a) [56].

Generally, these bulk materials are traded within regional markets due to their low economic value in terms of weight and the high costs of transportation [51]. This results in close physical urban and rural hinterland linkages. It is becoming increasingly clear that hinterlands supplying rapidly urbanizing areas are either running out of non-renewable natural resources or are facing serious environmental problems. According to Sing et al. (2012) [61], several Asian countries are already experiencing severe shortages of natural river sand and are struggling with the devastating consequences of sand mining, such as alteration of rivers, increased suspended sediments and erosion. Clays are often extracted from topsoil at the expense of fertile farmland. The extraction of limestone and basalt damages scenic places and landscape, causing habitat and biodiversity loss.

Thus, particularly in regions where urban areas are growing rapidly, a comprehensive understanding of urban-rural linkages is urgently needed to support integrated planning of urban and surrounding areas. However, only a few studies on material flow analysis (MFA) have been carried out to date considering urban-rural linkage issues; these have tended to focus on food and energy issues (Fritsche et al. 2015) [13]. With regard to construction materials, it is worth mentioning research by Binstock & Carter-Witney (2011) [2], who consider mining activities in the hinterlands of urbanized areas in order to discuss land use conflicts between growing settlements and mining areas. However, they do not provide material flow calculations and thus do not address direct linkages between urban material consumption and rural material supply. Nevertheless, there is a lot of existing knowledge on MFA concepts suitable for analyzing physical material flows induced by the built environment, such as buildings and infrastructure (see e.g. Müller et al. 2014; Augiseau, Barles 2017; Kennedy 2016; Schiller et al. 2017a) [46, 1, 23, 56]. Current approaches are either derived from macroeconomic statistics following a deductive approach (top down) or extrapolated from specific data with regard to elements of the built environment (bottom up). Top-down approaches (e.g. Müller 2006) [45] provide almost no classification by type of materials and cannot distinguish between different elements of the built environment such as buildings and roads. In contrast, bottom-up approaches (e.g. Ortlepp et al. 2015) [47] supply more detailed information in terms of materials but also in terms of spatial differentiation.

**Material flow analysis within the MAREX project**

Since the political reforms known as "Doi Moi" at the end of the 1980s, Vietnam's economy has developed very dynamically. Economic growth averaged seven percent between 2010 and 2017. The construction industry is one of the main contributors to the economic upturn. With the support of the central government, the development of internationally competitive metropolitan regions around Ho Chi Minh City and Hanoi is being promoted. Both cities are expanding rapidly on the basis of ambitious master plans and are devouring large quantities of construction minerals. However, there are no facilities to recycle construction and demolition waste (CDW) so the materials required are barely available in the cities. Inevitably there is big pressure on rural provinces in the surrounding hinterland, which become not only raw material suppliers to meet their own demand but also for these fast-growing urbanization hot spots.

It is particularly important that the extraction of raw materials is better aligned to the demand situation in the future. Due to the uncoordinated granting of licenses and a lack of monitoring, more aggregates and gravel are currently being produced than are necessary for the construction of buildings and roads in the region.

The main objective of the MAREX project is to make a contribution to sustainable development in Vietnam by improving the management of mineral resource extraction. For this purpose, four targets (see Figure 1) are addressed:

1. To enhance the knowledge base regarding environmental problems and land use change effects in regions caused by mining activities,
2. To improve the capacities of mining companies regarding the implementation of cleaner production technologies and the application of rehabilitation techniques of environmentally degraded areas in mining regions,
3. To introduce methods of material flow analysis in order to better forecast the demand side regarding the extraction of minerals and to foster better land use planning,
4. To establish a business-policy interface in order to support the sustainable management of mineral resource extraction.

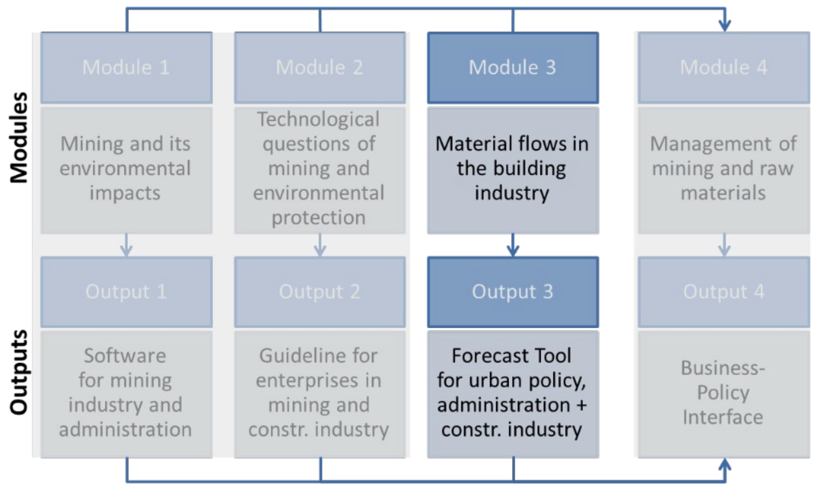


Figure 1: Modular structure of the MAREX project (Source: IOER 2015)

In order to take first steps towards responsible and more sustainable mining and allocation of mining licenses, a long-term estimation of the supply and demand for building minerals is needed. This means that the supply and demand of bulk non-metallic mineral construction materials within an urban region need to be quantified and analyzed in a comprehensive and transparent manner.

In this report we introduce the concept of a forecasting tool for calculating material flows in the construction industry, in the Hanoi metropolitan region and the province of Hoa Binh, developed within the MAREX project.[1] The forecasting tool is based on regional material flow analysis (MFA) methods and was elaborated in cooperation with the local mining and building industry as well as governmental authorities. The tool is not only relevant for the case study area, but is also transferable to other regions within and outside of Vietnam.

Material flow analysis models provide an approach to quantify the effects of specific measurements on potential changes in future demand for construction minerals. They are applied to describe metabolisms by quantifying material flows, material stocks and stock changes in a defined system, while keeping in mind a specific subject as well as specific spatial and temporal scales. In material flow analysis, two calculation approaches are possible: a top-down deductive approach and a bottom-up inductive approach. The bottom-up approach, which was applied in this study, provides information on both the quantity and quality of the required materials. With such information, direct references to settlement planning tasks can be established and planning areas can be integrated (e.g. infrastructure planning, resource planning, and land use planning) as required by Vietnam's current planning law.

By doing so, regional dependencies in urban demand for construction minerals and the rural supply of materials are quantified, qualified and discussed. Furthermore, we reflect resource conservation options following an integrative view on regional land use policies, cleaner production approaches and green building approaches that must be combined in order to find answers to the challenge of increasing resource consumption in an ongoing urbanization process.

[1] The essential elements of the concept have already been published in [73].

# 2 Methodology and dataset

## 2.1 System Boundaries and Process Chain Model

Worldwide, most materials stocked in the built environment have been used for buildings and roads. In Japan, for example, nearly 43% of in-use construction materials are stocked in buildings and 26% in roads [63]. Since the material composition as well as the stock dynamics of these two subsystems differ significantly, they are calculated and analyzed separately. Due to the spatial system boundaries of the case study area, the model is additionally divided into two further subsystems, Hoa Binh Province and Hanoi, which are defined according to their administrative boundaries (see Figure 2).

As highlighted in Figure 2, the comparison and balancing of supply and demand within the system boundaries is fundamental in applying regional Material Flow Analysis. According to the European Commission (2010) [11] a mineral policy has to define “a clear statement of agreed objectives for the management of mineral resources which aim to ensure their supply to meet the needs for those minerals”. Only by integrated consideration and planning of demand and supply of raw materials, in particular regionally traded bulk minerals, can supply without bottlenecks on the one hand and unplanned overcapacities due to overexploitation on the other hand be guaranteed.

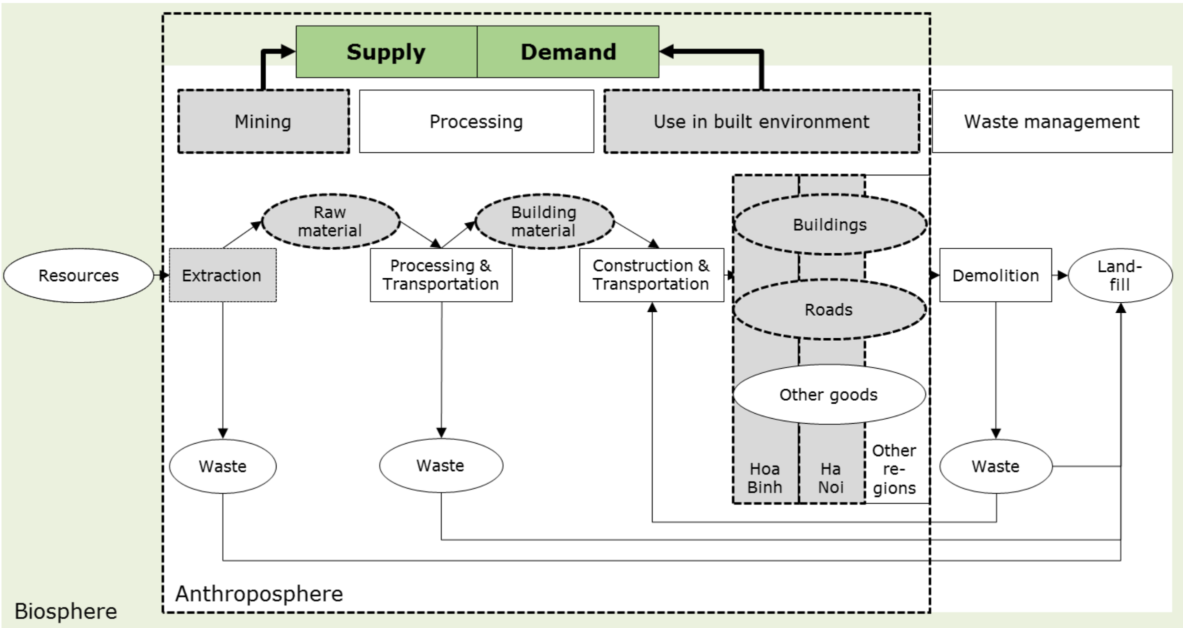


Figure 2. System boundaries marked with dotted lines and research foci in gray (Source: own illustration)

The structure to define and relate the supply of and demand for construction minerals can be described with a process chain that is separated into four steps which the materials pass through: mining, processing, use in the built environment, and recycling and disposal (Figure 2). In order to establish a long-term sustainable circular economy that requires fewer or almost no primary materials and in which waste serves as a new input and substitutes for conventional primary raw materials, special focus must be placed on seamless linkage of the phases of demolition, recycling, processing and (re)use in the built environment. However, if demand for materials exceeds the amount of recyclable waste flows generated, detaching primary materials is not possible. This phenomenon is especially true for rapidly urbanizing regions.

Along the four process steps, the development of material flows from natural capital stocked in the biosphere to construction materials and finally to construction and demolition waste (C&D waste) can be systematically traced, quantified and qualified. Through “Mining”, natural resources are extracted from the biosphere and enter the anthroposphere as raw materials. The quantity of raw materials extracted but not yet processed represents the supply side of our model. “Processing” is an intermediate step, which further transforms raw materials into construction materials by different processing steps. “Use in the built environment” defines the demand for materials, which is determined by construction activities such as new construction, reconstruction and upgrading. Once incorporated into the built environment, which is subcategorized into infrastructure and buildings, the material is stocked there for several decades before it is released again as C&D waste. The waste might be disposed of or, ideally, recovered and used again to produce new construction materials or other products.

The minerals that go through the process steps described are subject to change. The process starts with raw materials such as stones, sand or clay, which are processed into products such as cement and then into ready to use construction materials such as concrete. At the end of the lifetime of buildings and infrastructure, the material accumulates as construction waste and is processed into recycled material unless it is disposed of in landfill or somewhere in nature. Thus, each process step is associated not only with a change of location but also with a transformation in the sense of modification of qualitative properties of the materials. The quantities of raw material substances contained remain unchanged along the transformation steps, provided no losses due to outward transfer occur in the process-chain steps. If this approach is further extended to the processes between demolition and reuse by integrating knowledge about the building structure and the process technologies of waste treatment, a continuous MFA approach can identify and analyse direct relationships between inflows and outflows in the built environment (Schiller et al. 2017) [55].

This report primarily focuses on the two steps “Mining” (supply) and “Use in the built environment” (demand). In terms of material types, the focus is on bulk non-metallic construction minerals such as stones, sand and clay. Supply capacities are initially compared with demand for construction minerals at the level of cumulative quantities. At this level, no distinction is made between raw materials and construction materials. Only in a second step is a corresponding distinction made, whereby construction materials (concrete, cement, masonry bricks, asphalt concrete) are converted into raw materials (stones, sand, clay, others) taking into account typical material compositions and mix designs (see Table 1).

Table 1: Raw material contents of construction materials (Source: based on expert knowledge)

| | **Raw material components (in % based on the mass of the construction material)** | | | |
|---|---|---|---|---|
| Construction material | Stones (limestone, basalt) | Sand | Clay / Marl | Others (e.g. fly ash, water, asphalt) |
| Concrete, 4x6, grade 150 | 62 | 32 | 2 | 5 |
| Concrete, 1x2, grade 250 | 64 | 27 | 4 | 5 |
| Cement | 70 | | 30 | |
| Clay Bricks (Vertical kiln; banned until 2030) | | | 100 | |
| Clay Bricks (Tunnel kiln) | | | 80 | max. 20 |
| Clay Bricks (Hoffman kiln) | | | 30 | max. 70 |
| Fine asphalt concrete | 60 | 35 | | 5 |
| Rough asphalt concrete | 75 | 20 | | 5 |

## 2.2 Regional Material Flow Analysis (MFA) to calculate material demand

### 2.2.1 Bottom-up Material Flow Analysis (MFA)

A dynamic stock-driven bottom-up MFA approach is applied to calculate the material demand of the built environment [1]. In this study, we focus on material demand induced by buildings and roads, which represent the main consumers of non-metallic construction minerals [56]. Buildings are divided into domestic and non-domestic buildings, while roads are divided into road classes (RC) and pavement types (PT). In the case of buildings, the construction of new buildings is taken into account. In the case of roads, distinction is made between new construction and upgrading. Upgrading is defined as the transformation of an existing road from a low to a higher standard. For domestic buildings and roads we calculate the material quantities according to the calculation principles of bottom-up MFA (Figure 3). The calculation of material quantities induced by non-domestic buildings is based on assumptions about the material composition and construction activity of non-domestic buildings according to the corresponding characteristics of housing construction.

Bottom-up calculations are based on a description of material composition of individual elements of the built environment and respective metric measures of physical stock. The projections were carried out prospectively for the years 2015 to 2030, if metric measures were available. More detailed information on the calculation of the material stock and flows can be read in chapters 2.2.1 (buildings) and 2.2.2 (roads). For years in which quantification of material stocks and flows could not be carried out due to data gaps, we complemented our model by interpolations and assumptions on the percentage distribution of construction minerals stocked in domestic buildings, roads and non-domestic buildings, based on relevant literature [54], [63], [17], [16].

For the description of material quantities, material composition indicators (MCI) were developed. This allows information about material composition to be transferred into an indicator with metric information as reference values (e.g. kg/m²). The MCIs were developed and differentiated according to construction materials and then converted into raw material groups. This conversion enables comparison of stocked raw materials against the supply situation.

| **Typologies**<br>Elements | Measures | **Calculation Principle** | | | | |
|---|---|---|---|---|---|---|
| Domestic building types | New construction | MCI [kg/m²] | x | Floor area [m²] | = | kg |
| Non domestic buildings | New construction | general surcharge on domestic buildings [%] | | | = | kg |
| Road classes<br>Pavement types | New construction<br>Upgrading | MCI [kg/m²] | x | Road surface [m²] | = | kg |

Figure 3: Calculation principle of the bottom-up MFA model applied, differentiated according to the elements of the built environment considered (Source: own illustration)

### 2.2.2 Spatial dimension

Bulk non-metallic construction minerals are characterized by high volumes but low unit values (Wilburn, Goonan 1998) [69] and at the same time, are burdened by high relative costs of transportation (Pacheco-Torgal et al. 2014) [51]. Therefore, these materials are usually traded and consumed near to the place of extraction and processing; this generally results in regional-based markets with maximum transport distances of about 50 kilometers (Wilburn, Goonan 1998; Schiller et al. 2017) [69, 55]. Thus, acknowledging that flows of bulk construction minerals are predominantly managed regionally, direct linkages between regional hinterlands and urban areas can be described through a spatial reference model, as presented schematically in Figure 4.

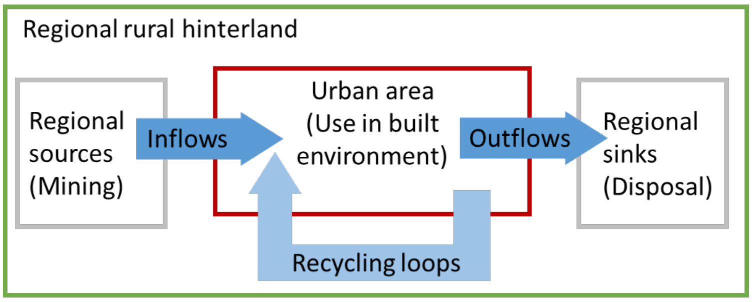


Figure 4: Spatial reference model for bulk non-metallic construction minerals (Source: own illustration)

## 2.3 Domestic buildings

### 2.3.1 Typology of domestic buildings

In Vietnam domestic buildings are subdivided according to their construction into permanent housing (all three main structural elements, supporting columns, roof and walls, consist of sturdy elements), semi-permanent housing (two out of three structural elements are made of sturdy categories), temporary housing (one of the three structural elements belonging to the sturdy category) and simple housing (all three structural elements are classified as flimsy) (see Figure 5 and Figure 6). Permanent domestic buildings can be subdivided into a) tubehouses (also called street- or shophouses), which is the most typical form of urban houses, b) detached houses (or villas), which are developing in many new urban areas, and c) apartment blocks, which are becoming increasingly important [66]. In our study, we only consider domestic buildings which contain significant quantities of mineral construction materials, such as permanent and semi-permanent houses. Temporary and simple houses are basically built up with light materials, such as sheet metal, wood, bamboo, etc., which are not relevant to our calculations.

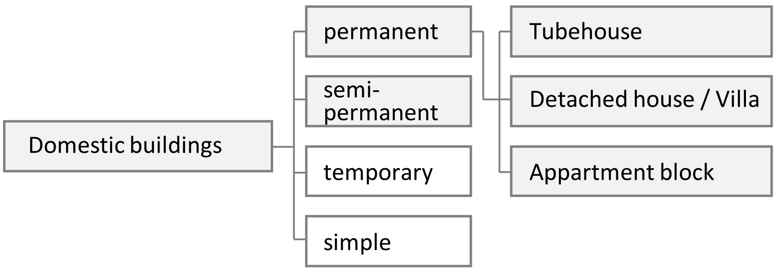


Figure 5: Classification of Vietnamese domestic buildings according to UN Habitat [66]
(gray: building types analyzed) (Source: own illustration)

#### Tubehouses

Tubehouse is one of several terms (also called shop-, street- or rowhouse) describing the most common domestic building type in Vietnam. Nowadays most of them are newer post-reform tubehouses, which commonly consist of three storeys. However, it is not unusual to stack these houses up to seven or even more storeys. Tubehouses are always narrow and on a long plot (usually 4 m by 25 m) and have 100 percent plot coverage. As the narrow façade always faces a street, the ground floor is sometimes used for commercial purposes. According to local regulations and urban planning codes, the height (or number of floor levels) of the houses is determined by the width of the street they face. They also comply with rules of setback, plot coverage ratio, overhang of balcony, and even color use. Street houses have been a type of contemporary housing that was largely designed by owners, rather than by architects or builders. Traditionally, this type of housing has been developed in most urban areas of Vietnam and has been built by owners. It is legal to design your own street house provided the total floor area is less than 250 m². Older pre-reform shophouses instead have a maximum of two storeys, a tile roof and usually a commercial ground floor [27].

**Detached houses and villas**

Detached houses are appearing in many new urban areas. In contrast to tubehouses, the floor area of detached houses is usually greater than 250 m², which is why they are mostly designed and built by architects and construction companies.

**Apartment blocks**

Apartments are the third preference due to their small footprint. The apartment is an emerging type of contemporary Vietnamese housing that has been introduced from overseas countries [20]. Apartments require complex construction methods and materials and have to comply with building regulations and codes. Although such multi-storey housing forms definitely entail disadvantages (loss of cultural heritage, abandonment of traditional building materials, etc.), they may be unavoidable given the high and dense population in rapidly urbanizing cities.


Figure 6: Typical domestic houses in Vietnam

### 2.3.2 Material Composition Indicators of domestic buildings

This is schematically presented for the MCIs of tubehouses. Depending on the building type, the number of case studies and synthesized MCIs per type varies between two and seven.

The definition of MCIs for domestic buildings is based on empirical analyses of case study (CS) buildings. For this purpose, planning documents and expert knowledge were evaluated by local architects. The planning documents included Bills of Quantities (BoQ), i.e. already prepared measurements of realized construction projects, as well as floor plans with supplementary information on the construction method of the buildings, from which the specific dimensions of the construction elements and buildings were calculated. The information aggregated in this way is described as specific MCIs in Figure 7.

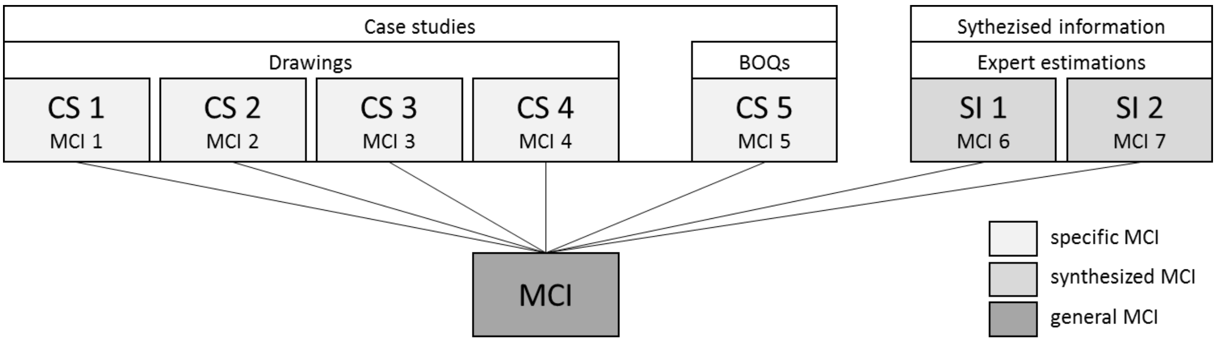


Figure 7: Schematic representation of the generation of MCIs for Vietnamese tubehouses (Source: own illustration)

In order to expand the empirical basis, expert knowledge was additionally used for orientation values of the material intensity of the domestic building types considered, with a focus on concrete and brick (synthesized MCIs). Two experts were consulted in open interviews. Both have a background in architecture and civil engineering, hold leading positions in planning offices and have several years of experience in housing construction. Working with respective indicators is a basic tool in their everyday planning work. Table 2 gives an overview of the building types analyzed and the analysis methods used.

Table 2: Empirical concept to define MCI for Vietnamese domestic buildings (Source: own editing)

| **Building type** | **Analyses based on*** | | |
|---|---|---|---|
| | **Drawings** | **Bill of Quantities** | **Expert Interviews** |
| Tube house | 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 analyzed or the number of interviews conducted.

Based on the surveys carried out according to Table 2 MCIs were defined for each building type by simple averaging (Figure 8, Table 3).

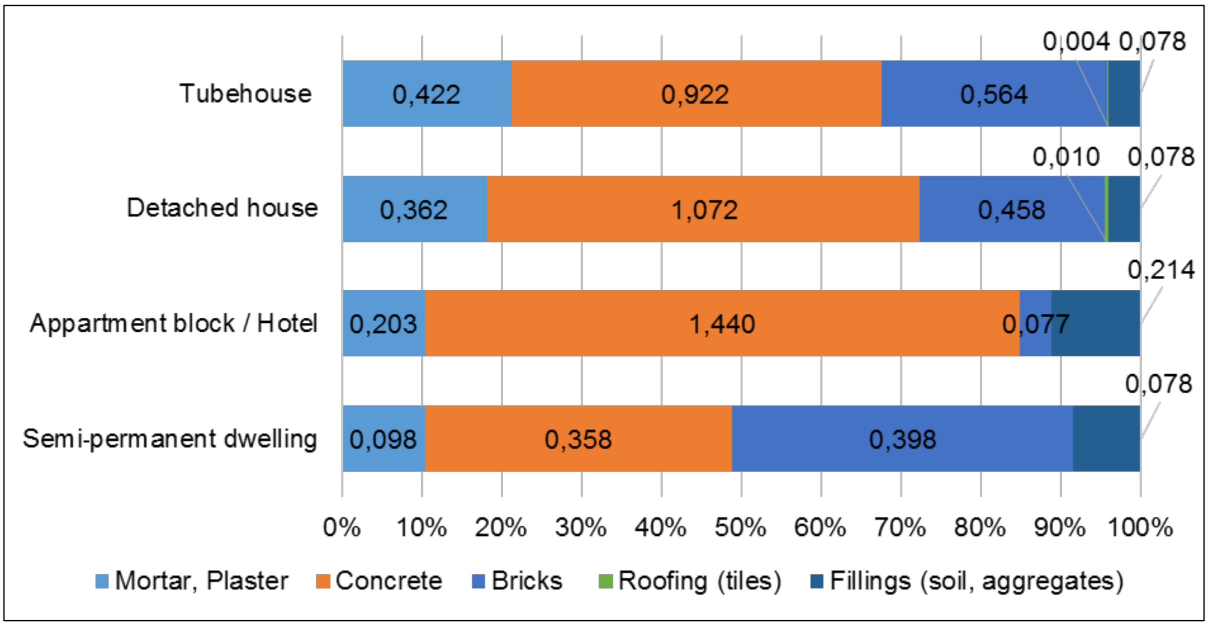


Figure 8: Material Composition Indicators (MCI) of typical domestic buildings in Vietnam classified by building materials – percentage shares (scaling of the axis) and absolute values in t/m² floor area (numerical values on the bar segments) (Source: own illustration)

The amount of non-metallic mineral construction materials per square meter of floor area differs only marginally between the building types Apartment Block, Detached House and Tubehouse. Semi-permanent buildings, on the other hand, require significantly less material per square meter of floor area due to their lightweight construction. Since the foundations of the building types were also taken into account, the MCIs for semi-permanent buildings also contain relatively large amounts of concrete.

Demand for building materials refers to building materials such as concrete, bricks, asphalt concrete, etc. The supply of building materials, on the other hand, is provided as raw materials such as sand, stone or clay. In order to enable a linkage between supply and demand, the MCIs are also classified according to raw materials (Table 3). This is based on information on raw material contents of building materials based on literature references (see Table 1). Losses that may occur during the production of building materials are not taken into account.

Table 3: Material Composition Indicators (MCIs) of Vietnamese domestic building types classified according to construction materials and raw materials (Source: own calculation)

| | MCI [t/m² floor area] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Construction 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 house | 0.10 | 0.36 | 0.40 | - | 0.08 | 0.19 | 0.27 | 0.99 | 0.08 | 0.93 |

### 2.3.3 Building stocks

Considering data availability reported in official statistics, we use net floor area to describe stocks and flows of domestic buildings.

We calculate the domestic net floor area from the number of inhabitants multiplied by per capita living space. In Vietnam, both can be taken from official documents at provincial level as current data (population Hanoi: [17]; population Hoa Binh: [18]; floor area per person Hanoi and Hoa Binh: [14]) and as future data (population Hanoi: [34] population Hoa Binh: [7]; floor area per person Hanoi: [8]; floor area per person Hoa Binh: [14]). The value calculated in this way corresponds to the total domestic net floor area. Differentiation according to building types can be made on the basis of data from the Household Living Standard 2014 [14], which makes corresponding statements as percentages related to current and future housing stock (planning data). The formula [F1] describes the resulting algorithm for calculating floor area from the housing stock.

For the years in which quantification of material stocks and flows could not be carried out due to data gaps, we complemented our model by interpolating.

$$FA\ [m^2] = population\ [pers.] * \ floor\ area\ \left[\frac{m^2}{pers.}\right] * \ building\ type\ [\%] \qquad [F1]$$

### 2.3.4 Material demand for new construction

Neither data on new construction nor data on demolition are available from the statistics. For this reason, new construction activities are determined using the balance sheet method. Housing stock for two consecutive years (t1 and t0) is calculated using data from the corresponding years. Under growth conditions, the need for new construction results from the difference between the stock at times t1 and t0 plus the required replacement new construction following building demolition. Demolition is calculated using demolition rates, based on assumptions about the average life of residential buildings. According to Huang et al. [19] an average life expectancy of 30 years is assumed for residential buildings. This results in a demolition rate of 3.3%. Formula [F2] summarizes the resulting calculation rule.

$$new\ construction\ _{t0-1}[m^2] = (FA\ _{t1}[m^2] - FA\ _{t0}[m^2]) + FA\ _{t0}[m^2] * demolition\ \text{ratio}\ [\%] \qquad [F2]$$

The stock in events t1 and t0 is differentiated according to building types (see previous remarks). Thus the material demand can also be calculated according to building types using the balancing procedure [F3]: $material\ demand\ _{t0-1}[t] = \sum_{i=1}^{n} new\ construction_{t0-1\ i}\ [m^2] * MCI_i\ [\frac{t}{m^2}]$ [F3] with:

MCI(i) material composition indicator for building type “i” [t/m²domestic net floor area]

New construction $t_{0\text{-}1i}$ number of newly constructed domestic buildings of building type “i” [m²domestic net floor area]

## 2.4 Non-domestic buildings

### 2.4.1 Material demand for new non-domestic construction

With regard to non-domestic buildings, there is no evidence that would allow quantification of the building stock and its dynamics. Similar gaps in knowledge are noted in the literature in a large number of studies relating to different country contexts (an overview is provided by [48]). In many European countries the amount of non-domestic building stock, in terms of floor space, is about the same quantity as the amount of floor space in domestic buildings [48]. Appropriate estimates are available for the building stock in China [19]. Ortlepp et al. [47] describe non-domestic buildings in the German building stock as "the other half of the city". Based on this work, we also assumed in this article that the size of the non-domestic building stock corresponds to that of domestic buildings. We transferred these assumptions to the dynamics of the existing stock and the composition of the materials. The total demand for building materials for all buildings is thus calculated from the demand for new construction of domestic buildings multiplied by two.

## 2.5 Roads

### 2.5.1 Typology of roads

The first characteristic refers to the connecting and accessing function of roads. This is differentiated by road classes (RC). The second characteristic refers to the physical structure of roads. This is closely related to pavement types (PT). The RC classification in Vietnam is described in TCVN 5729: 2012 [40], TCVN 4045:2005 [35], TCVN 10380: 2014 [43] as well as TCVN 104: 2007 [36] (see Table 4 and Figure 9). A distinction is made between highways, national, district, commune and urban roads. These categories are further divided into subcategories. For national roads, topographical features (terrain types, TT) are also considered for further differentiation. For the RCs differentiated in this way, average road widths can be described using national technical standards, differentiated according to pavement and roadbed (see Figure 12).

Table 4: Road classes in Vietnam (Source: based on TCVN 5729:2012 [40], TCVN 4045:2005 [35], TCVN 10380:2014 [43], TCVN 104:2007 [36])

| | | **Standard** | **Class / Type** | **Average width [m]** | |
|---|---|---|---|---|---|
| | | | | **pavement** | **roadbed** |
| **Highways** | | TCVN 5729:2012 [40] | 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 |
| **National Roads** | Plain / hilly terrain | TCVN 4045:2005 [35] | 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 [35] | Class III (60Km/h) | 6 | 9 |
| | | | Class IV (40Km/h) | 5.5 | 7.5 |
| | | | Class V (30Km/h) | 3.5 | 6.5 |
| | | | Class VI (20Km/h) | 3.5 | 6 |
| **Rural Roads – District Road** | | TCVN 10380:2014 [43] | Type A | 3.5 | |
| | | TCVN 4054:2005 [35] | Class IV | 5.5 | 7.5 |
| | | | Class V | 3.5 | 6.5 |
| | | | Class VI | 3.5 | 6 |
| **Rural Roads – Commune Road** | | TCVN 10380:2014 [43] | Type B | 3.5 | 5 |
| | | | Type C | 3 | 4 |
| **Urban Roads** | | TCVN 104:2007 [36] | Class 2: Major urban main street | 30 | 30 |
| | | | Class 3: Main secondary urban street | 27 | 27 |
| | | | Class 4: Collector street | 12 | 12 |
| | | | Class 5: Internal roads | 7 | 7 |

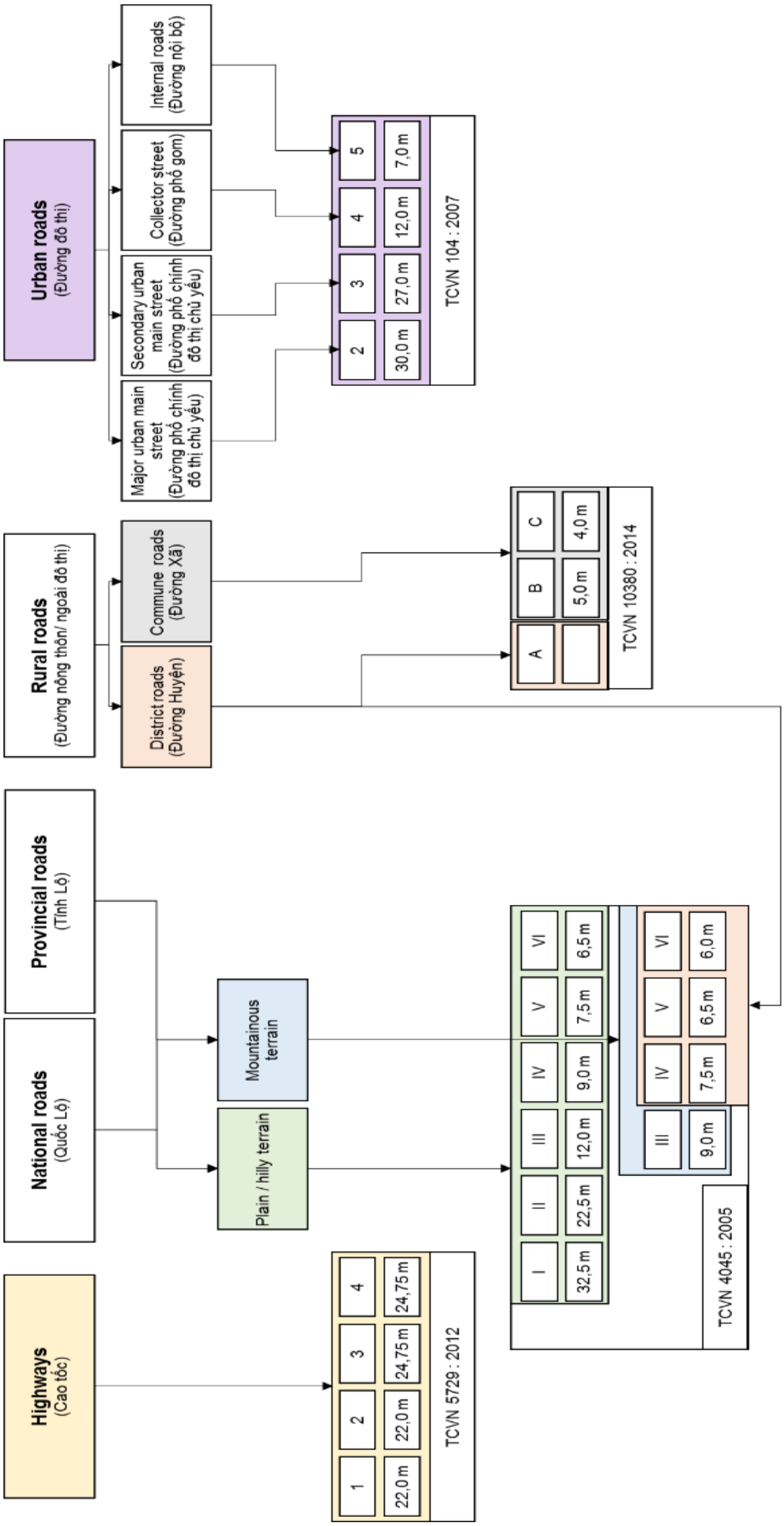


Figure 9: Road classes and average road widths including roadbed for motorized vehicles according to technical standards (Source: own illustration, based on TCVN 5729:2012 [40], TCVN 4045:2005 [35], TCVN 10380:2014 [43], TCVN 104:2007 [36])

Typical pavement types (PTs) in Vietnam are Asphalt Concrete, Cement Concrete, Bitumen Treated Crushed Stones, Crushed Stones and Soil (see Figure 11 and National Standards and Circulars such as [34], [35], [36], [38], [39], [40], [41], [42] [43]). Each PT consists of a specific number and combination of layers and is designed for an average lifespan (e.g. [36]) as shown in Table 5. On this basis, specific material compositions (MCIs) can be described.

Table 5: Average lifespans of typical pavement types in Vietnam (Source: based on TCVN 5729:2012 [40], TCVN 4045:2005 [Ministry of Transport and Communications, 2005: TCVN 4054:2005: Highway – Specifications for design], TCVN 10380:2014 [43], TCVN 104:2007 [36])

| | Asphalt Concrete (high class) | Asphalt Concrete (low class) | Cement Concrete | Bitumen Treated Crushed Stone | Crushed Stone | Soil |
|---|---|---|---|---|---|---|
| **Average lifespan** | ≥ 10 years | ≥ 10 years | ≥ 10 years | 4-7 years | 3-4 years | 3-4 years |

**Asphalt Concrete**

The **Asphalt Concrete Pavement** or **Bê tông nhựa (BTN)** is an exceptional pavement type for the present study. In terms of layer construction, it is useful to distinguish between two asphalt concrete pavement types: asphalt concrete road surface for high-class roads and that for low-class roads, where high-class and low-class roads are national highways and the rest, respectively. The pavement structure for high-class roads consists of four layers. Based on expert knowledge, the layer structure of low-class roads is different in that it consists only of three layers (Layer 1: Rough Asphalt concrete, Layer 2: Aggregate crushed stone type 1, Layer 3: Natural aggregate stone).[2]

**Cement Concrete**

**Cement Concrete Pavement** or **Bê tông xi măng (BTXM)** is a very resistant and relatively high class pavement type in Vietnam. To prepare for paving, the subgrade – the native soil on which the pavement is built – must be graded and compacted. Preparation of the subgrade is often followed by placing a subbase – a layer of material that lies immediately below the concrete. The essential function of the subbase is to prevent the displacement of soil from underneath the road surface. There are two methods for paving with concrete – slipform and fixed form. In slipform paving, a machine rides on treads over the area to be paved – similar to a train moving on a set of tracks. Fresh concrete is deposited in front of the paving machine which then spreads, shapes, consolidates, screeds, and float finishes the concrete in one continuous operation. This operation requires close coordination between the concrete placement and the forward speed of the paver. In fixed-form paving, stationary metal forms are set and aligned on a solid foundation and staked rigidly. Final preparation and shaping of the subgrade or subbase is completed after the forms are set. Forms are cleaned and oiled first to ensure that they release from the concrete after the concrete hardens. Once concrete is deposited near its final position on the subgrade, spreading is completed by a mechanical spreader riding on top of the preset forms and the concrete. The spreading machine is followed by one or more machines that shape, consolidate, and float finish the concrete. After the concrete has reached a required strength, the forms are removed and curing of the edges begins immediately.

[2] Based on expert knowledge (Yen).

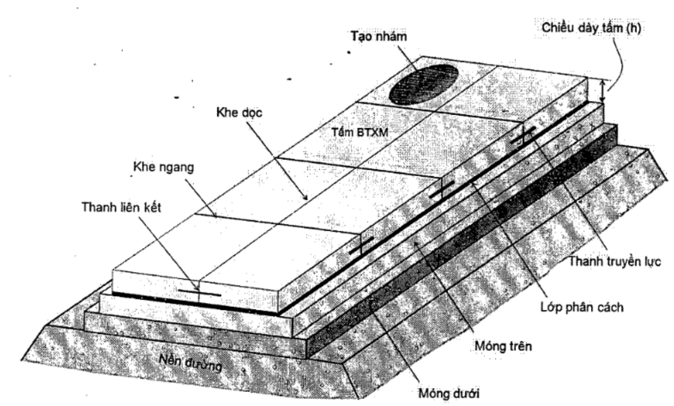


Figure 10: Cement concrete pavement slab [decree no. 3230/QD-BGTVT; http://www.sgtvt.danang.gov.vn/images/stories/3230_QD_BGTVT.pdf]

### Bitumen Treated Crushed Stones

**Bitumen Treatment Pavement**, also known as **Đá dăm nhựa,** is very different from asphalt concrete. The term "bitumen treatment" means that crushed stones or aggregate crushed stones are treated with bitumen. The most common method is to spray bitumen on the compacted crushed stones or let the crushed stones absorb the bitumen. By that method, the stone layers will be reinforced by bitumen in order to obtain more strength. In Vietnam, this type of road surface is very popular, with the name "Đá dăm thấm nhập nhựa" or "Láng nhựa".

### Crushed Stones

**Aggregate Crushed Stones**, also known as **Cấp phối (CP)** is more common than **Crushed Stones** or **Đá dăm (ĐD)** because it does not require well collected stones (e.g. special granularity, stones with same size, high resistance, assorted flatness, etc.). Meanwhile, by requiring aggregate crushed stones, stones of different sizes can be used to construct material layers. But as there is no significant difference between the two pavement types in term of material consumption, CP and ĐD are considered the same in this study.

### Soil Pavement

Structural **Soil** or **Đất** is composed of crushed stone (in Hoa Binh, typically limestone or basalt) narrowly graded and with clay loam.


Figure 11: Typical pavement types in Vietnam

### 2.5.2 Material Composition Indicators of roads

MCIs for roads are defined based on local norms and regulations (see Figure 13). The information was mainly obtained from Circular No. 1776/BXD-VP "Descriptions and guidance manual of construction estimating norms – Construction phase" [31] and Circular No. 1784/BXD-VP "Descriptions and guidance manual of the application of construction materials" [32].

Non-metallic construction minerals obtained by mining are mainly used to construct road pavements. The roadbed, which serves as a foundation, consists of soil excavated in the near surroundings of the construction site. Thus, this material demand is not considered in our calculations, even though it plays an important role in terms of quantities, as seen in Figure 12.

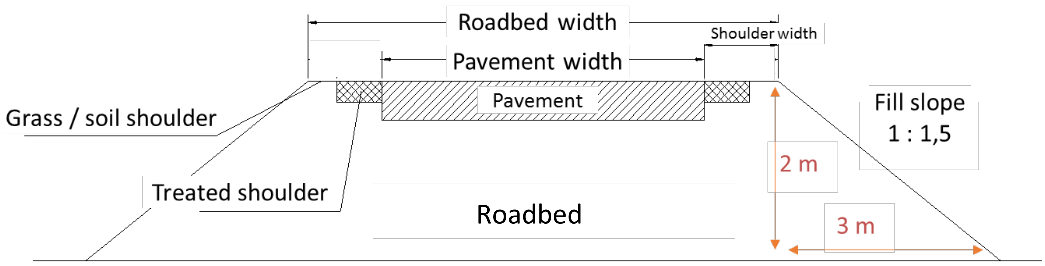


Figure 12: Schematic illustration of a filling cross section (Source: own illustration)

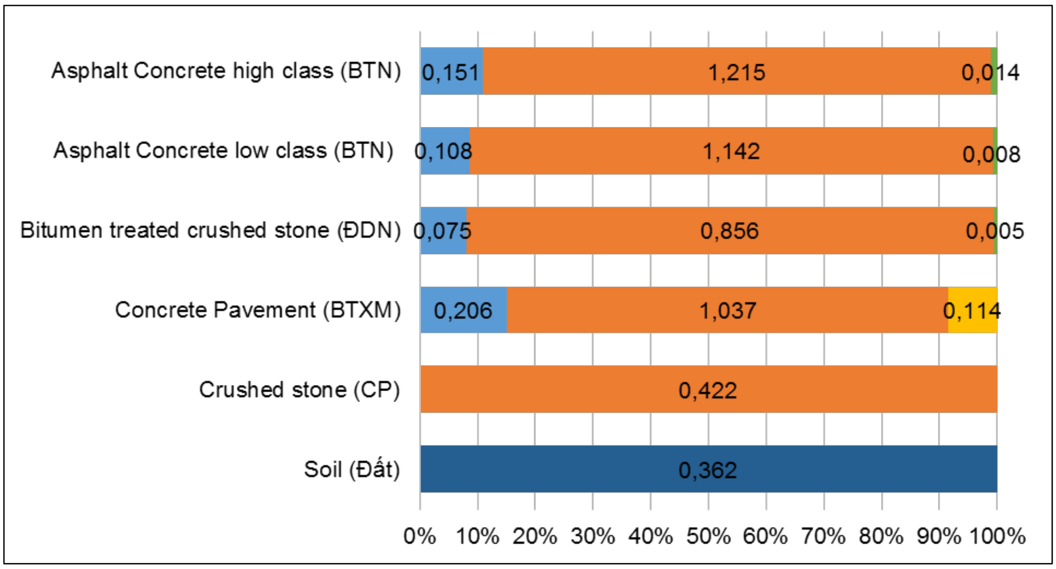


Figure 13: Percentage of construction materials investigated differentiated by typical Vietnamese road types and MCIs in t/m² (Source: own illustration)

### 2.5.3 Road stocks

Data on the length of the road network are only available for certain years and in varying degrees of differentiation. Road stock data differentiated by road classes was only made available for Hoa Binh for the years 1995 and 2003 to 2016 and for Hanoi only for the year 2016. Additional differentiation of the data according to pavement types is possible for Hoa Binh for the years 1995, 2012 and 2016 and for Hanoi for the year 2016.

If time series were available (Hoa Binh from 1995 to 2016), the data gaps were closed by interpolation. If no time series were available and therefore no interpolation was possible (Hoa Binh from 2016 and Hanoi total), no statement on the length of the road network could be generated.

### 2.5.4 Material demand for new construction, renovation und upgrading

The main calculation model for the quantification of material demand for roadworks is based on the road length, the respective pavement width depending on the road class and terrain type (see Table 4) and the MCIs depending on the pavement type (see Figure 13).

Annual material demand can be differentiated into material demand for new construction activities (construction and renovation) and upgrading activities. Since a different demolition ratio and cascade-like upgrading were considered for each pavement type, the road area (RA) for both the new pavement [F4] and the upgrading [F5] was calculated separately for each pavement type according to the following formulas [F4, F5]. The total mass of minerals required annually can thus be calculated using formula [F6].

$$new_{\ t0-1}[m^2] = (RA_{\ t1}[m^2] - RA_{\ t0}[m^2]) + (RA_{\ t0}[m^2] - RA_{\ up.,t0-1}[m^2]) * demolition\ ratio\ [\%] \quad \text{[F4]}$$

$$upgrading_{\ t0-1}[m^2] = \sum_{j=1}^{5} RA_{\ up.,j,t0-1} \quad \text{[F5]}$$

$$material\ demand_{\ t0-1}[t] = (new\ construction_{\ t0-1}[m^2] + upgrading_{\ t0-1}[m^2]) * MCI\ [\tfrac{t}{m^2}] \quad \text{[F6]}$$

with:

Preconditions: $new_{t0-1} - \sum_{i=1}^{4}(new_{i,to-t1}) \geq 0$ and $PT_{i,t0-1} \geq 0$

$$RA_{\ up.,j,t0-1} = \begin{cases} PT_{up.,j,t0-1} & if \quad PT_{up.,j,t0-1} < new_{t0-1} - \sum_{i=1}^{4}(new_{i,to-t1}) \\ new_{t0-1} - \sum_{i=1}^{4}(new_{i,to-t1}) & if \quad PT_{up.,j,t0-1} \geq new_{t0-1} - \sum_{i=1}^{4}(new_{i,to-t1}) \end{cases}$$

$PT_j$ Pavement type under consideration j = {1, 2, 3, 4, 5}, with 1: Soil, 2: Crushed Stones, 3: Bitumen Treated Crushed Stones, 4: Cement Concrete, 5: Asphalt Concrete

For years in which no information on the length of the road network could be generated, the annual demand for construction minerals for roadworks was calculated from the percentage distribution of the total demand for the domestic building sector, the non-domestic building sector and the roadwork sector.

As a bottom-up calculation could only be carried out for the years up to 2016 for Hoa Binh and exclusively for 2016 for Hanoi due to the poor availability of data on road network length, assumptions had to be made for the years after 2016. For both Hoa Binh and Hanoi, it was assumed that the share of material demand for road construction in total material demand (residential buildings (DB) + non-domestic buildings (NDB) + roads) would remain unchanged from 2016. Differentiation of the material requirements for roadworks according to material types (sand, limestone/basalt, cement, asphalt binder and soil) was achieved by multiplying the total annual requirements for mineral materials for roadworks by generic MCIs, which result from the sum of all MCIs weighted according to pavement types.

## 2.6 Supply calculation

Commonly, the process of legislating and managing mineral construction materials supply and thus granting mining licenses has two main frameworks, legislative and administrative (institutional). In Vietnam, the responsibility for the supply of minerals for the production of cement lies with the Ministry of Natural Resources and Environment (MoNRE); all other licenses concerning the extraction of construction minerals are managed by the provincial departments (DoNRE).

In the international discussion, the word reserve refers to a mineral resource that has valid planning permission for extraction [25]. The Register of Legal Mining Businesses, provided by the DoNRE, reports on licensed mine reserves, the reserves in licensing procedures, the maximal annual mining output and license periods.

In this study, we consider the reserves of mineral resources licensed in 2015 in order to estimate the regional supply situation. For the presentation of supply capacities from 2015 to 2030 we added together the already licensed reserves, and those which were in the licensing process in 2015, of all registered mining companies located in Hoa Binh Province (see [F7]). The periods of the registered licenses range from 3 to 44 years and average 25 years. For our study we simply assumed that no new licenses will be issued until 2030. In terms of material types, the focus is on bulk non-metallic minerals corresponding to the construction products discussed in chapter 2.3, namely stones (basalt and limestone), sand and clay.

$$supply\ capacity\ [t] = \sum_{i=1}^{n} licensed\ material\ reserves_i\ \text{[t]} \quad \text{[F7]}$$

with:

licensed material reserves $_i$ material reserves (licensed and in the licensing process, state 2015) of mining company “i” located in Hoa Binh Province in tons [t]

# 3 Results

## 3.1 Case study area

Referring to the case study area, Hoa Binh Province represents one of the main producers of construction minerals and covers not only its own but additionally a share of Hanoi’s demand. Based on Hoa Binh’s Master Plan for Exploitation and Use of Minerals for Construction Materials, this share is on average about 35% (Resolution 76/2013/NQ-HDND) [6] but varies depending on mineral raw material type between 0% for sand, 19% for clay and 60% for stones. The remainder of Hanoi's demand is covered by Hanoi itself and other neighboring provinces with reserves of construction minerals, as shown in Figure 14.

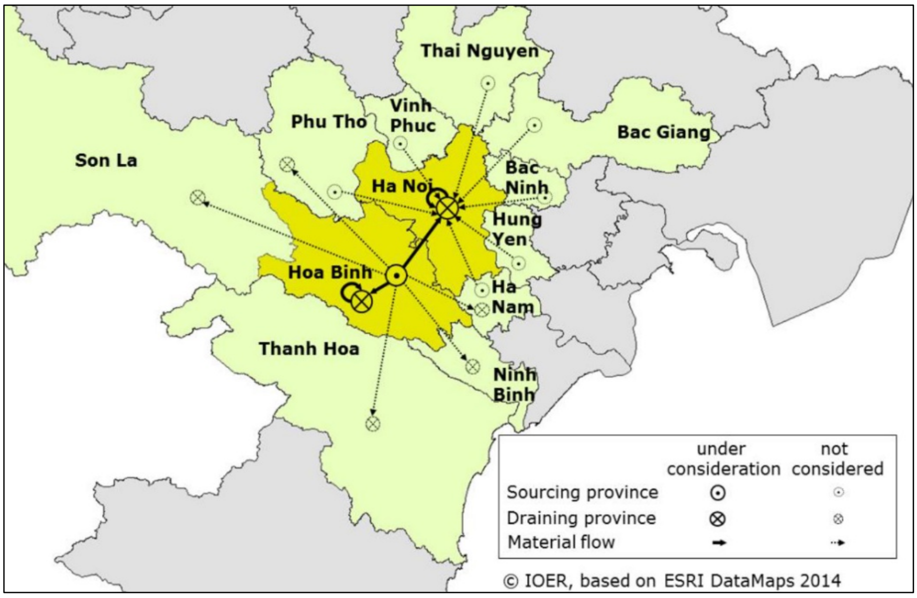


Figure 14: Spatial representation of regionally traded non-metallic construction minerals and supply relations within the case study area (Source: IOER Dresden, based on ESRI DataMaps 2014)

## 3.2 Demand and supply for construction minerals

Annual demand for construction minerals can be calculated using the databases and formulas presented in chapter 2.2 ([F3] for buildings and [F6] for roads). On this basis, a three year moving average [28] of the annual demand for construction minerals covered by Hoa Binh province was calculated and accumulated over the period from 2015 to 2030, as shown in Figure 15. In addition, Figure 15 shows the mining reserves of Hoa Binh Province in 2015 divided into licensed reserves and reserves that were still in the process of being licensed. If no new licenses are issued, the available quantity will reduce over the years according to material requirements.

Demand for construction minerals will rise continuously until 2030, mainly due to a strong urbanization dynamic and socio-economic changes, which are reflected in declining household sizes, population growth and an increasing consumption of floor space per capita. The increase is mainly in Hanoi and less in the hinterland province of Hoa Binh. Despite the rising demand trend, Figure 15 indicates that material capacities will far exceed demand in the case study area (Hanoi and Hoa Binh Province).

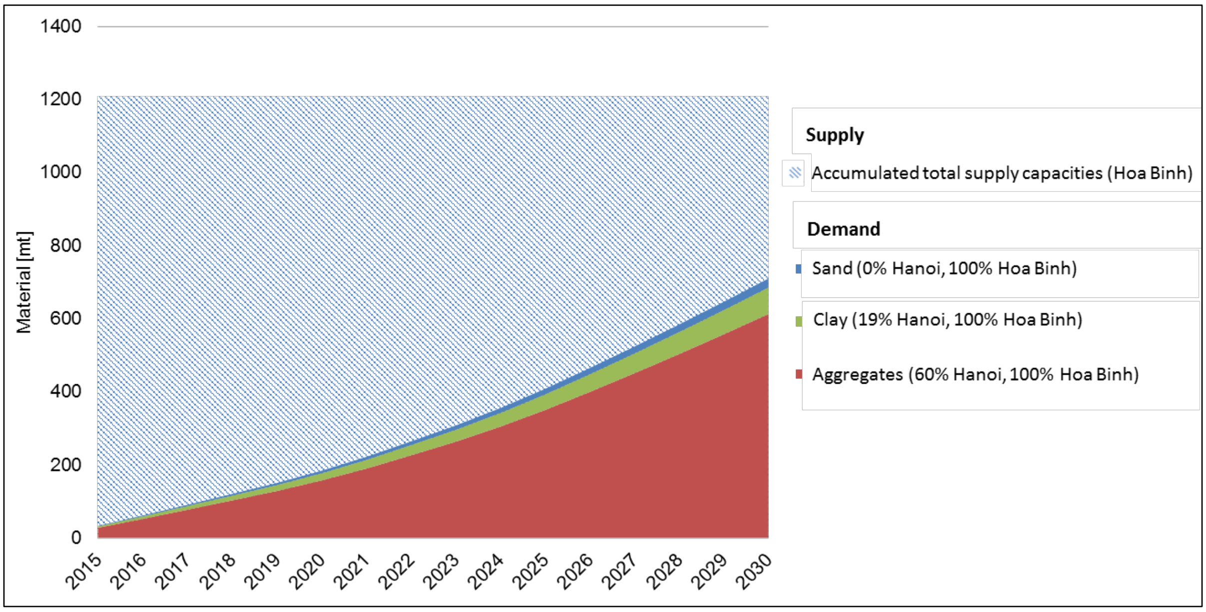


Figure 15: Accumulated construction mineral demand and supply capacities of Hoa Binh Province (stones + clay + sand; 3-year average; reference year 2015; Source: own calculation)

Such aggregated calculations of the demand and supply of building minerals are often used as a basis for securing raw material supplies. However, at this level of differentiation, it is not only possible to understand the development of demand for each specific material group, but also to consider different supply relationships per material. It is not possible to interpret and discuss the figure, as the information contained therein is not sufficiently differentiated. For this purpose, a differentiated examination and comparison of materials subdivided into material types is necessary. The Register of Legal Mining provides differentiated information on sand, limestone, basalt and clay reserves in Hoa Binh Province. The calculation of the demand for these materials can only be plausible, comprehensible and transparent using a bottom-up approach. According to the Master Plan for Exploitation and Use of Minerals for Construction Materials (Resolution 76/2013/NQ-HDND) [4], it was assumed that Hoa Binh covers different shares of Hanoi's total demand for aggregates (60%), sand (0%) and clay (19%) without affecting its own needs.

Since the orders of scale between aggregates, clay and sand are very different, Figure 16 provides a more detailed overview of the supply and demand situation calculated for 2030. In the graph the accumulated material demand for the period 2015 to 2030 is compared to calculated supply (available licensed capacities) in the province. Here, very different patterns can be observed in the different raw material categories. Due to its scarcity, sand cannot be exported beyond the borders of Hoa Binh Province, assuming that the needs of the province are given priority. However, the available capacities are even not sufficient to satisfy this quantity. Thus, sand is scarce and needs to be imported additionally into the province. Clay remains within the provincial borders to cover own needs and is partly exported to Hanoi. However, existing capacities only cover the province's own requirements. Demand from Hanoi cannot be met without opening up new mining areas. In the case of gravel and aggregates, the licensed supply volumes clearly exceed the demand. There is obviously sufficient capacity available here. Nevertheless, it should be noted that, firstly, the extraction of raw materials is already causing considerable conflicts with other land uses and, secondly, continuation of the high demand for raw materials beyond 2030 is to be expected. Here, too, there is a need to look for reduction potentials.

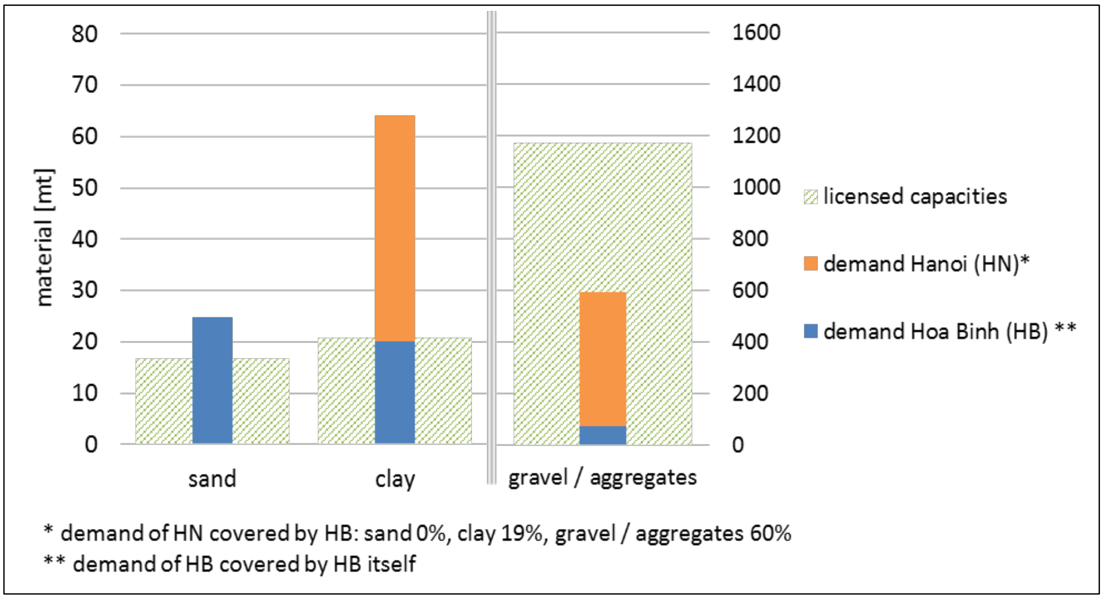


Figure 16: Balancing of supply and demand according to material types (Source: own calculation)

The development of demand and potentially available reserves of aggregates (limestone, basalt), sand and clay over time are presented in Figure 17, Figure 18 and Figure 19.

Figure 17 shows that Hoa Binh has very large reserves of stones (limestone and basalt), which will even exceed accumulated demand by 2030. According to local construction and mining companies, limestone extracted in Hoa Binh has a particularly high density and can thus be used almost as an equivalent to basalt, which usually is much denser. The demand for aggregates (limestone and basalt) in the construction sector considered in this model essentially consists of aggregates for road pavements, for fillings and for the production of concrete. In addition, limestone was considered for the production of cement.

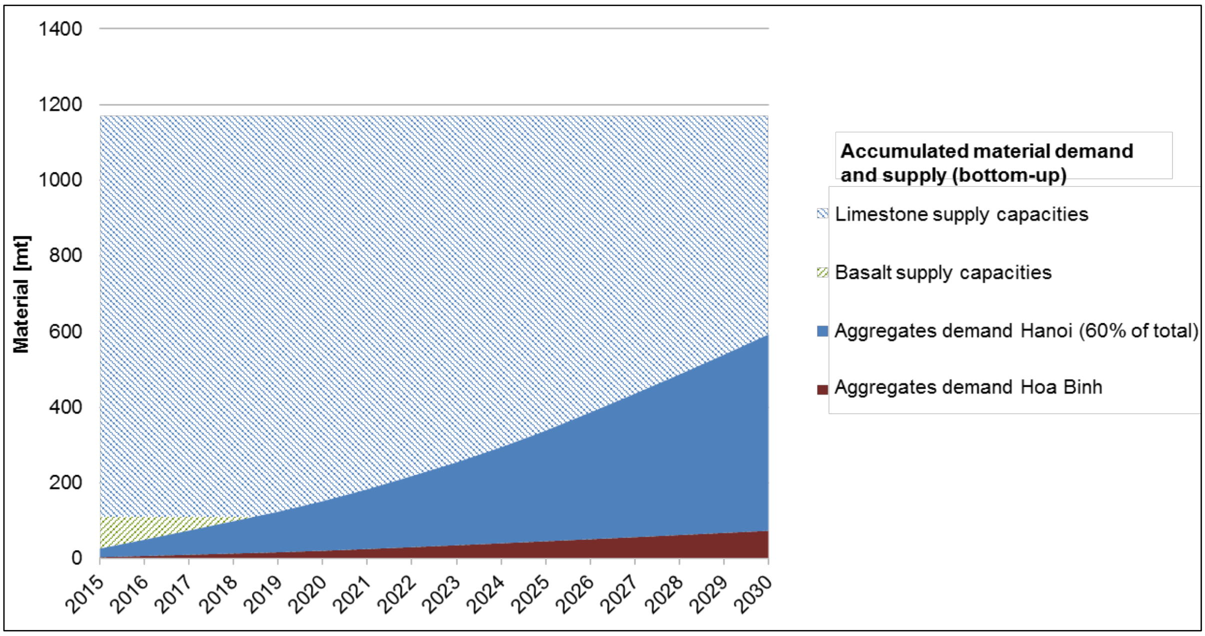


Figure 17: Accumulated demand for aggregates covered by Hoa Binh Province in relation to Hoa Binh's supply capacities (3-year average; reference year 2015; Source: own calculation)

Another pattern can be seen in Figure 18 for natural river sand. Hoa Binh has sand reserves which may not meet the demand of the construction sector even in the near future. Currently, new technologies for producing artificial sand, which corresponds to the properties of natural river sand, are not yet being applied. Thus, Vietnam, like many other countries in the world, is experiencing a severe shortage of sand. The information extracted from the Mining Masterplan (Resolution 76/2013/NQ-HDND) [6], that 0% sand will be delivered to Hanoi and all sand will remain in the region may soon not correspond to reality anymore due to the profitability of trading sand. According to local entrepreneurs, sand is even transported as far as Singapore, where the market price is particularly high.

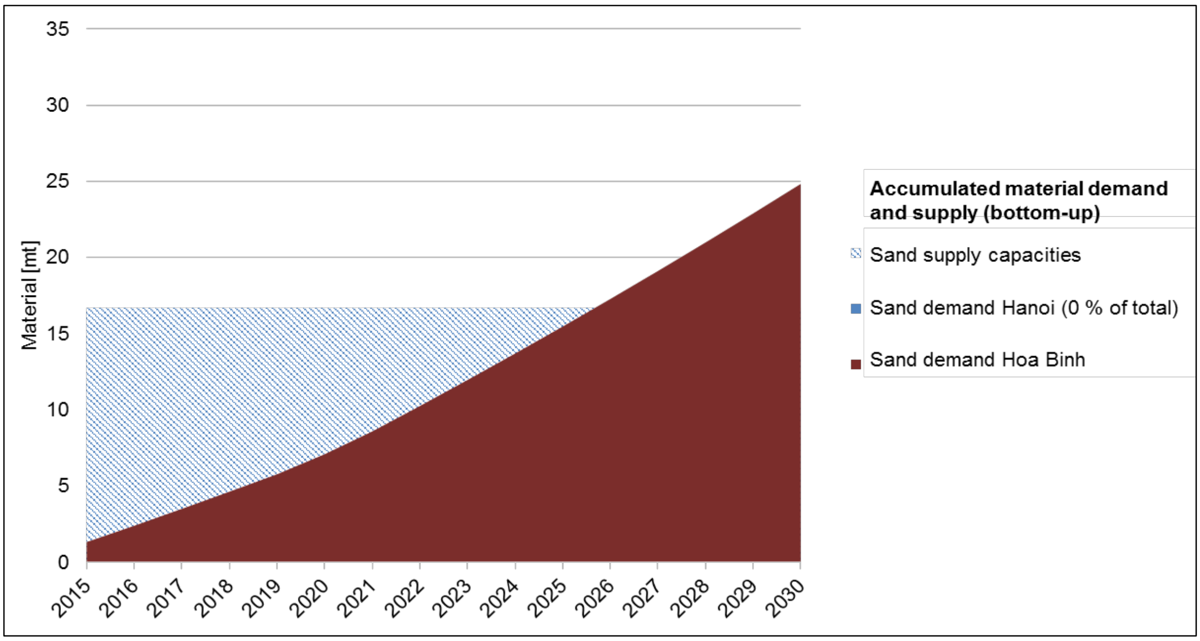


Figure 18: Accumulated demand for sand covered by Hoa Binh Province in relation to Hoa Binh's supply capacities (3-year average; reference year 2015; Source: own calculation)

The development of supply and demand for clay can be seen in Figure 19. According to the Mining Masterplan (Resolution 76/2013/NQ-HDND [6]), we assumed that 19% of Hanoi's clay demand would be covered by supplies from Hoa Binh. The province's own needs will not exceed reserves until 2030. However, the total quantity to be covered is increasing rapidly, so that in the near future the reserves licensed in 2015 will be used up.

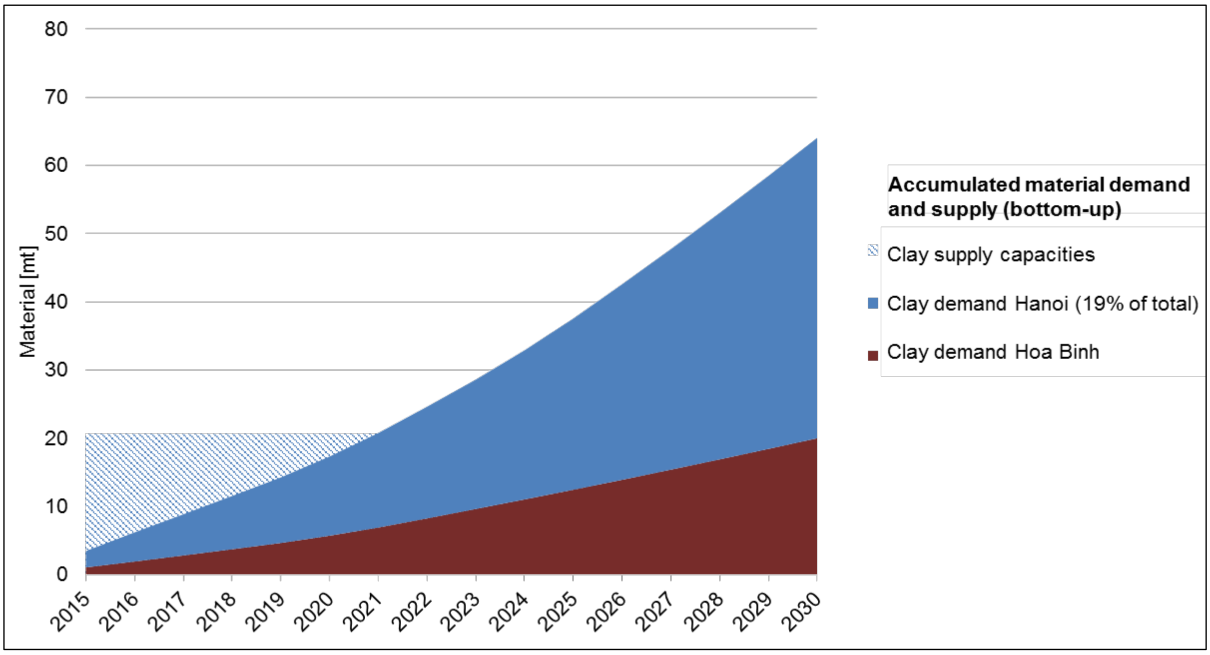


Figure 19: Accumulated demand for clay covered by Hoa Binh Province in relation to Hoa Binh's supply capacities (3-year average; reference year 2015; Source: own calculation)

For clay it becomes clear that the Mining Master Plan overestimates the possibilities of supplying material to Hanoi. For these scarce resources, especially for sand, it can be assumed that the discrepancy between supply and demand not only leads to unavoidable imports from more remote areas, but also to illegal mining activities in the supplying hinterland areas, such as Hoa Binh Province. When even the needs of supplying regions can no longer be covered, serious bottlenecks and a struggle for this scarce resource will arise.

However, this differentiated analysis not only offers the possibility to describe supply bottlenecks in detail, but also to describe material substitution potentials in the built environment and to quantify their effects on demand to be covered by the hinterland.

# 4 Discussion

## 4.1 Uncertainties and Plausibility

MFA is a comprehensive tool to depict materials within the built environment in a differentiated way. However, coefficient-based MFA models are structurally fraught with uncertainties. Laner et al. (2014) [24] distinguish various sources of uncertainty in MFA models, such as statistical variation, variability in parameters over space and time, unpredictability, subjective judgments, scientific disagreements, linguistic imprecision and approximations due to model simplifications and assumptions. Ortlepp et al. 2016 [49] propose making a distinction between parameter uncertainties due to input data and model uncertainties related to outcomes. In this study, parameter uncertainties refer in particular to the generation of MCIs (empirical database, weighting variability in parameters over space and time) as well as to partially incomplete statistical data. Model uncertainties summarize all assumptions and simplifications that distinguish the model from reality. In this study, these include assumptions about material requirements for non-domestic buildings, lifetime and supply relationships.

In order to take all uncertainties into account and recognizing that a relatively conservative approach was chosen for our calculations, a flat rate of ±33% was considered based on a corresponding analysis of Schiller et al. (2017b) [57].

On the other hand, due to their simplicity and in order to illustrate rough trend projections, we conducted comparative top-down calculations. Such calculations can serve as references to assess uncertainties of coefficient-based bottom-up calculations, which consider specific technological and regional characteristics of the built environment. Top-down approaches are based on national economy-wide data on material consumption per capita and are related to population figures as a reference value.

Economy-wide Material Consumption Indicators, such as domestic material consumption (DMC) and raw material consumption (RMC), are calculated and reported for most of the world’s nations but do not allow any further differentiation into material types, e.g. (construction) minerals. Focusing on minerals, only statistics on material extraction are available, for which coverage is still unsatisfactory, in particular with regard to non-OECD countries where huge data gaps can be identified, as is the case for Vietnam (Lutter et al. 2016a) [26].

The most differentiated dataset for the purpose of this study is provided by WU and Dittrich (2014) [72] and reports the amount of minerals extracted annually from 1980 to 2013. Commonly, minerals are divided into construction and industrial minerals. In terms of quantity, industrial minerals are less important, representing exemplarily in Germany only 6% of total abiotic extraction. Against this background, we assume that also in Vietnam 94% of the statistically reported mineral extraction per capita comprises construction minerals. Construction minerals here include asphalt, common clay and clay for bricks, crushed stone, igneous rock (basalt, basaltic lava, diabase, granite, porphyry, etc.), limestone, marble and travertines, sand and gravel, sandstone, slate including fill and roof slate (WU, Dittrich 2014; Lutter et al. 2016a) [72, 26].

In a regional context, it can be assumed that extraction is consumption, since construction minerals are traded within regional markets. At national level, the extraction data has to be adjusted on the basis of the formula below.

$$Consumption\left[\frac{t}{pers.}\right] = Extraction\left[\frac{t}{pers.}\right] + Import\left[\frac{t}{pers.}\right] - Export\,[\frac{t}{pers.}]$$

In the case of Vietnam, the statistically reported figures on import and export of construction minerals are incomplete, so the difference between imports and exports represents only a negligible fraction of the quantity extracted. For demand projections after 2013, two trend developments were calculated, comprising (a) a linear trend projection, and (b) no change from the status-quo consumption in 2013. Data on population development are taken from the Statistical Yearbooks of Hoa Binh Province and Hanoi as well as the Population Projections for Viet Nam 2009-2049 (General Statistical Office Viet Nam 2011a) [27]. The total annual demand for construction minerals is calculated by multiplying the data on population with material consumption per capita at a regional scale.

Given (a) a polynomial increasing trend projection, and (b) no change in consumption from 2013, the demand for construction minerals was calculated top-down through multiplying per capita consumption with population figures. In both cases, the demand for construction minerals will steadily rise until 2030. Even by considering no increase in consumption (b), total material demand will rise from 18,218,000 to 22,464,000 tons per year in the period between 2015 and 2030 merely due to the projected population growth.

Figure 20 shows a comparison of our model calculations, the uncertainty considerations (±33%) and the top-down calculations. Due to our rather conservative approach and contrary to the top-down calculations, we consider a correction of our results upwards (+33%) to be meaningful.

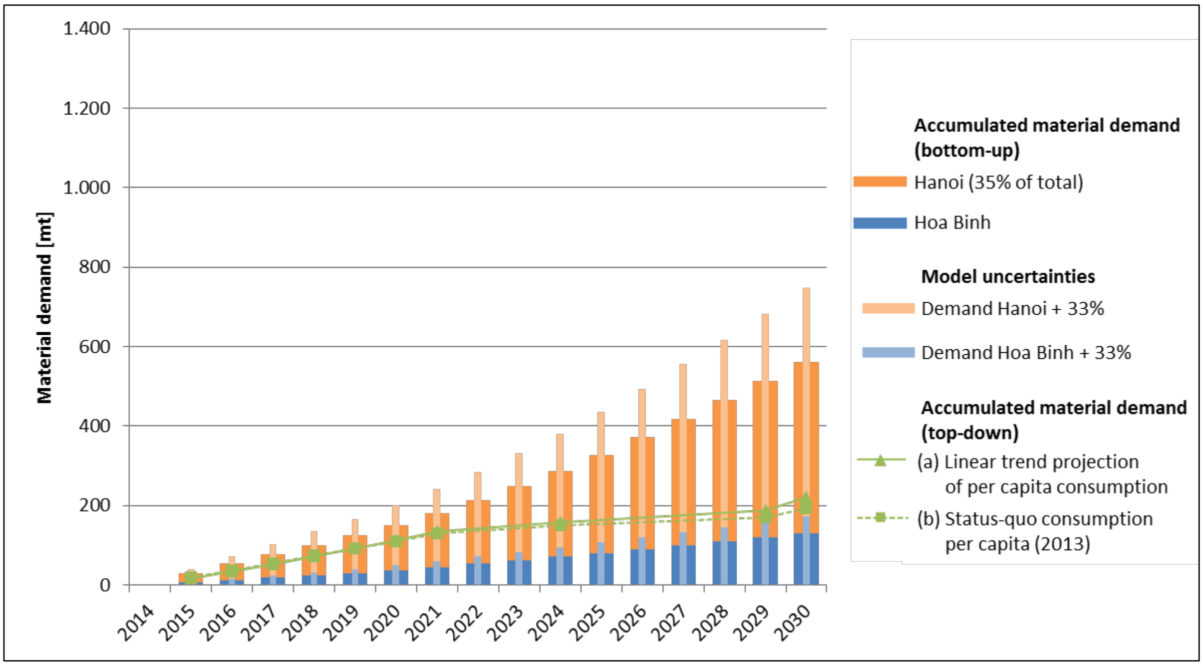


Figure 20: Accumulated construction mineral demand (stones + clay + sand) of Hoa Binh Province and Hanoi covered by Hoa Binh Province from 2015 to 2030 with uncertainty considerations (Source: own illustration)

Against the backdrop of the socio-economic development planning of Vietnam, investment in infrastructure is expected to be further fostered in the near future. The Socio-Economic Development Strategy (SEDS) defines the long-term goals to be attained within a 10-year period and serves as the basis for the formulation of sectoral and local development plans (such as mining, transportation, housing, energy, telecommunication, etc.). It identifies infrastructure development as one of three crucial areas of development (World Bank 2016) [70]. The Provincial Master Plans on Socio-economic Development for Hanoi City (Decision 1081/QD-TTg) [52] and Hoa Binh Province (Decision 917/QD-TTg) [53] define explicit midterm objectives, such as "to build a complete and modern infrastructure system (upgrade national highway 6, build Hoa Lac-Hoa Binh city road, several new roads and bridges)" in Hoa Binh Province. With regard to the ambitious development goals and above all due to upcoming upgrading and maintenance activities, which are closely intertwined with an increasing stock of materials in buildings and infrastructure, we assume that per capita demand for construction minerals will rise then stabilize in the near future.

## 4.2 Potentials of the approach

Coefficient-based bottom-up MFA is a powerful tool, with which detailed and goal-oriented data can be generated. Depending on the aim of the study, such data can serve as an important basis for discussion of political decisions, as a basis for planning or as a foundation for awareness raising. Explicitly describing the current situation as well as future scenarios by supporting them with data is particularly important.

### 4.2.1 Securing raw materials

The management of mining is a multi-actor and a multi-level task. According to Östensson (2005) [50], governments at national and regional level, the mining industry, local communities, and non-governmental organizations (NGOs) are the key actors in this field of activity. Governments have responsibility for finding a balance between protecting the natural environment and conserving, in particular, non-renewable finite resources and promoting material economic growth. For these reasons a regulative system is necessary. An explicit and data-based description of the current situation and future scenarios is necessary to establish and support such a regulative system.

For that reason, this study aimed to describe and compare the demand and supply situation in Hanoi and the hinterland province Hoa Binh in a quantitative and qualitative manner and to identify possible supply bottlenecks. The results generated are addressed to all parties involved in the management of mining, regional planning and raw material security planning for the construction industry.

The comparison of the expected long-term supply and demand situation differentiated by raw material groups has shown that the majority of the mining reserves licensed in 2015 and currently in the licensing process are limestone reserves. It is expected that there will be no supply bottlenecks for limestone in the longer term. Rather, institutional, organizational and economic challenges to environmentally friendly and socio-efficient mining of aggregate play a role in this context. Established forms of licensing, by which many small companies are granted licenses, have encouraged the plundering of mineral stocks and companies mutually interfering with one another. Best Practice in mining technology is, for the majority of mining operators, not possible because of the short-term planning of licenses and the too small mining sites that do not allow the building of ramps, berms, slopes and benches [60].

The results were compared with existing planning documents and discussed with mining companies and planning authorities. It has been found that the Master Plan for Exploitation and Use of Minerals for Construction Materials of Hoa Binh Province (Resolution76/2013/NQ-HDND) [6] only covers very short-term planning horizons of five years, which significantly affects long-term licensing strategies. The demand development is projected according to the trend of growth in consumption in previous years, yet statistics show that consumption of construction materials has not followed a pattern and is highly dependent on state investment and the real estate market. The MFA approach presented in this study is ideally suited to simulating longer-term demand developments that are not only based on trend forecasts but on actual expected changes in population, the construction industry, urban planning and strategic development objectives.

### 4.2.2 Substitution potentials – using the example of brick construction

However, the approach also provides the opportunity to describe tangible solution-oriented scenarios quantitatively and qualitatively, such as substitution potentials of construction minerals in buildings and infrastructure and the respective effects on the supplying regional hinterland. This is only possible if the data generated are differentiated, transparent and empirically substantiated. For the substitution discussion, it is important that material demand and supply can be distinguished between material type and supply relationship.

Material substitution potentials were simulated on the basis of technical substitution options in a simplified estimation procedure [74]. Substitution options for conventional concrete and traditionally manufactured bricks (solid vertical kiln bricks) were considered. The substitutes considered and listed in Table 6 represent technical alternatives documented in the literature, but do not claim to be complete. The percentages given in Table 6 indicate how the substitutes affect a change in demand for raw materials in relation to the respective traditional building product category. The substituted conventional construction material (conventional concrete and solid vertical kiln bricks) is regarded as a reference. The analyses of the substitution potentials are exemplified for the domestic building stock of Hanoi and Hoa Binh Province in total. This is methodically implemented by adjusting the MCIs used to calculate the material flows in accordance with the assumptions listed in Table 6 by replacing the corresponding traditional construction materials with the substitutes.

Table 6: Calculation basis for the quantification of material substitution potentials (Source: own editing)

| Conventional building product | Substitute | Changes in recipe (material savings / additional material demand) in M.-% | | | | | |
|---|---|---|---|---|---|---|---|
| | | Sand | Coarse aggre-gates | Cement | | Clay | Other materials |
| | | | | Lime (70 M.-%) | Marl (30 M.-%) | | |
| Conventional concrete | seashells (V1) [12] | - 20% | | | | | |
| | | | - 50% | | | | |
| | artificial sand (V2) [21] | - 50% to - 70% | | | | | |
| | RC-aggregates (V3) [5] | | - 90% | | | | |
| | fly ash (V4) [62] | | | - 28% | - 12% | | |
| | carbon fiber concrete (V5) [59] | - 50% | - 50% | - 35% | - 15% | | - steel, + carbon fibers |
| Solid vertical kiln bricks (100% clay) | hollow concrete bricks (65 Vol.-% air filling) (V6) [29] | + 10% | + 20% | + 3.5% | + 1.5% | - 100% | |
| | hollow tunnel kiln bricks (57 Vol.-% air filling) (V7) [33] | | | | | - 65% | + 9% fly ash |
| | hollow Hoffmann kiln bricks (57 Vol.- % air filling) (V8) [33] | | | | | - 87% | + 30% fly ash |
| | Sand-lime bricks (V9) [44] | + 89% | | + 6% | | - 100% | |
| | Aerated concrete bricks (V10) [9] | 7% | + 7% | + 4% | 1% | - 100% | |
| | RC aerated concrete bricks (V11) [15] | 2% | + 7% | + 4% | 1% | - 100% | + 30% fine-grained construction waste |

Figure 21 presents the results of the substitution calculations for the 11 variants listed in Table 6. They relate to cumulative demand for construction materials from the construction of domestic buildings in Hanoi and Hoa Binh Province between 2015 and 2030. It is assumed that substitutes will be used, starting from 2020, using the variants under consideration. In all variants the demand for natural raw materials decreases. Depending on the variant, the savings are between 2 and 20%.

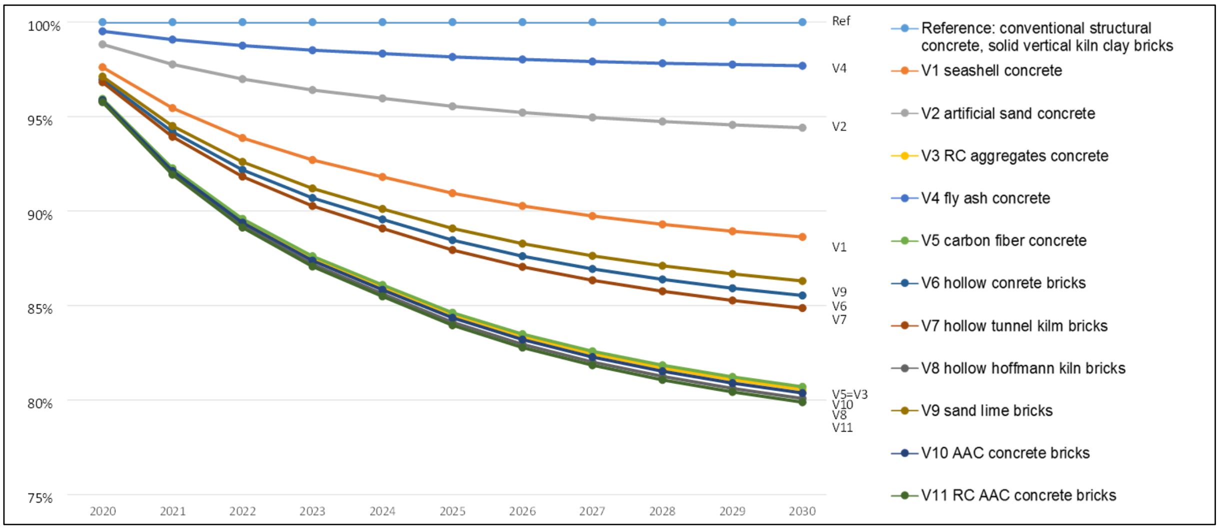


Figure 21: Cumulative raw material saving potentials development of accumulated construction mineral demand for domestic buildings in Hanoi and Hoa Binh (2015-2030, starting the use of substitutes by 2020) (Source: own illustration)

The savings are achieved by replacing materials (e.g. clay replaced by concrete) in combination with technological changes (e.g. solid bricks replaced by hollow bricks). Combinations of the considered variants are possible (e.g. use of RC aggregates in concrete components combined with innovative brick alternatives). This allows savings of up to 40% of the natural raw materials used to be calculated. In reality, the potential is probably lower, since new technologies are already being used that are not taken into account in the calculations.

The savings shown in Figure 21 do not differentiate between types of raw materials. This differentiation is made in Figure 22, where the savings are shown as absolute values (negative values in the figure). While the savings for clay brick variants relate exclusively to clay (substances that are not significant in terms of quantity are not taken into account here), there are clear differences for concrete variants. Variants 3 and 5, for example, achieve comparable savings effects; while in variant 3 the savings relate exclusively to aggregates, in variant 5 these are distributed among cement, aggregates and sand.

Since the Vietnamese government issued a ban on traditional brick production in vertical kilns until 2030 (Decision No. 15/2000/QD-BXD) [30], a gradual change-over to Hoffmann kilns and Tunnel kilns has taken place, which allows modification of the material composition of bricks and thus a reduction in clay demand. With this ban, and at the same time due to the promotion of concrete brick production, the amount of concrete in buildings is expected to rise further. This phenomenon can be seen in Figure 22. The graph shows all shifts in demand between alternative and natural raw materials. If bricks are produced with alternative materials, the demand for such materials increases (e.g. additional demand for sand aggregates and cement in different degrees in Variations 6, 9, 10, 11). Since new technologies are being introduced at the same time as the change of material, the mass of additional requirements is significantly lower than the savings.

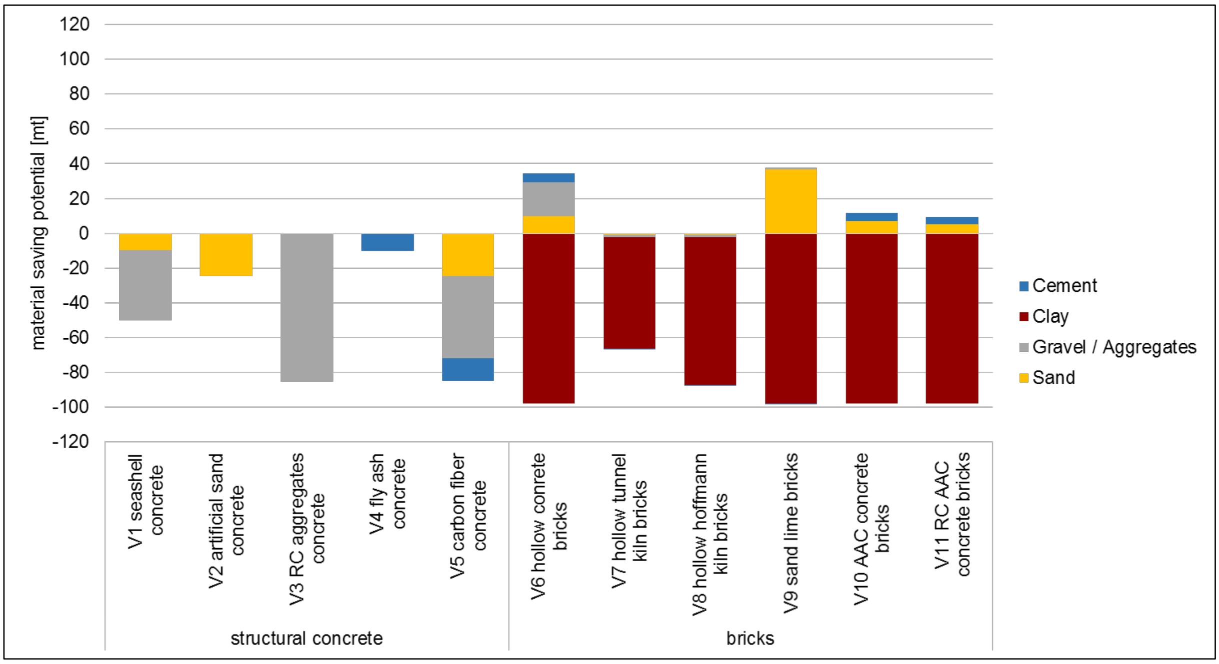


Figure 22: Variations in the accumulated material substitution potential for the development of the domestic building stock in Hanoi and Hoa Binh Province (2015–2030) in relation to conventional construction methods (Source: own illustration)

In particular, a shift towards higher sand demand can be regarded as critical. The Ministry of Construction (MoC) commented in a press release in 2017 that “Vietnam may run out of construction sand by 2020 if domestic demand for the resource continues to exceed the country’s total reserves” (Tuoi Tre News 2017) [64]. Several countries around the world are experiencing severe shortages of natural river sand and are developing and applying new technologies for producing artificial sand to cope with the increasing scarcity (Joel 2010) [20]. There is also keen interest on the part of Vietnamese mining companies to push the technology of artificial sand production in stone mines. Other alternative sources for river sand might be crushed and screened waste glass, recycled copper slag and sea sand (Sing et al. 2012) [61].

# 5 Conclusion

Using an MFA approach, supply and demand patterns can be quantified and qualified in an urban regional context and described along process chains. This allows urban-rural linkages resulting from supply and demand for construction minerals to be estimated.

Since the case study area is a rapidly growing and urbanizing area that is strongly dependent on primary raw materials, special focus was placed on the process steps “Mining” and “Use in the built environment”. It is obvious that dependence on primary materials cannot be a long-term environmentally friendly solution and that “sustainable mining” sounds like a paradox. However, a more sustainable circular economy which requires fewer or almost no primary materials and in which waste (output) serves as a substitute for conventional primary raw materials (new input) only functions if demand for new structures can be kept relatively low. As long as demand for materials exceeds the amount of recyclable waste flows generated, an entire detaching of primary materials is not possible.

With the method of bottom-up MFA presented, material requirements for future construction processes can be analyzed in detail. Extending the approach by including a regional component makes it possible to link detailed calculated material requirements with planning questions around supply of natural resources. Trends in urbanization indicate that demand for materials will remain high in the long term. Furthermore, experience from highly developed countries shows that this demand will not fall even after the urbanization dynamic has flattened out; as living standards rise and the populations of cities increase, so does the need for housing and infrastructure [58]. It is therefore imperative to find ways to secure supply and at the same time deal responsibly with regional resources. Quantified urban-rural linkages can provide a sound basis for this.

Against this background, the main advantage of the chosen process chain approach, which juxtaposes demand and supply, is to strengthen an integrated view between settlement development in demand-generating urban areas and land use planning in supplying hinterlands. Thereby it is important that the MFA approach can differentiate according to materials and construction raw materials and has the necessary prerequisites for a consistent process chain. Continuous MFA, which takes into account technical knowledge about material transformations throughout the process chain, offers the necessary access here.

The results of the future development of both trends – supply and demand for construction minerals – indicate that in the near future the increasing demand for sand and clay will no longer be met by the supply. Uncertainties cannot be avoided with any model that attempts to depict reality through assumptions and simplifications. This must be demonstrated as far as possible. On the one hand, by transparent description of the method and the data used and, on the other hand, by discussion or, at best, quantification of the associated uncertainties. Taking the model uncertainties into account, it seems probable that demand will rise sharply in the coming years. Only by matching the supply and demand situation can illegal and thus uncontrollable extraction of raw materials be counteracted and a controlled material supply can be ensured. There are basically two windows of opportunity to balance demand and supply in the long term.

On the one hand, sustainable mining has to be fostered. This includes less threats to natural beauty and diversity, steady control of mining sites, long-term mining planning and a sound licensing system. It is important that sufficient licenses are granted to make illegal, unregulated mining businesses less profitable, and that more is invested in Best Practice mining technologies. Furthermore, there is an urgent need for tough and consistent action against illegal mining activities. Not only by enacting laws (e.g. Directions No. 16/2003/CT-TTg and No. 29/2008/CT-TTg), which enhance the control of illegal sand mining in the country and suspend or stop all illegal sand mining activities, but above all by monitoring implementation of the laws and imposing penalties in cases of non-compliance [10].

On the other hand, there is the possibility of reducing demand for mineral construction materials. In view of population growth and the increase in prosperity associated with urbanization, an absolute reduction in demand for construction minerals is not expected. However, by integrating construction planning, urban planning and material supply planning, demand for specific (non-renewable) materials can be influenced. For example, by fostering green building strategies, the demand for construction minerals could be reduced in favor of renewable raw materials, such as bamboo and wood, or secondary raw materials, such as industrial waste and recycling materials.

The example substitution calculations show that materials science can make a significant contribution to this if the already known potentials are consistently exploited. A multitude of possibilities must be integrated into a holistic concept of a circular economy. This must take into account the availability of natural resources as well as the availability of the substitutes presented. In addition, further aspects must be taken into account, above all effects with regard to climate-relevant emissions. But considerations must not stop at technological questions. These must be linked with socio-economic issues and more fundamental issues of inventory development, which should also include sufficiency approaches, such as extending the lifespans of buildings. Much of this can be discussed and quantitatively substantiated with the approach presented.

The exploitation and production of each material – renewable or not – is linked to environmental impacts, which can vary greatly depending on regional conditions. In order to evaluate substitution potentials in terms of their sustainability a combination of practical assessment tools and approaches (such as an Ecosystem Service Approach, Life Cycle Assessment, Ecological Footprint Approach, etc.) needs to be elaborated in further research activities.

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Tamara Bimesmeier, Pham Thi Viet Anh, Klaus Dieter Oswald, Wolfgang Riedel, Georg Schiller, Petra Schneider

**Issue 5:** **Regional material flow analysis**
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**Issue 7:** **Planning for the responsible extraction of natural aggregates**
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**Issue 8:** **Legal framework for environmentally sound mining in Vietnam**
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**Issue 9:** **The MAREX Alliance**
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Bernhard Müller, Paulina Schiappacasse, Peter Wirth, Anh Minh Vu

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This booklet is a result of MAREX project:
Management of Mineral Ressource Extraction in Hoa Binh Province –
A Contribution to Sustainable Development in Vietnam

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ISBN 978-3-933053-44-2