Resource-saving in buildings through material substitution: A preliminary study of structural dependencies

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Abstract
Around the world, building stocks are the dominant consumers of mineral resources. Mining activities for the supply of construction materials can lead to conflicts in land use. In order to minimize such sources of conflict, we need improved knowledge of material consumption in the built environment. For this, we can make use of material flow analysis (MFA), which in turn requires the determination of material composition indicators (MCIs). Usually, such indicators are defined for a building type. Currently, there is a lack of research on the impact of material substitution on these MCIs as well as studies on the potential for resource-saving that take technical issues into account. This contribution describes a preliminary study on material substitution in six different reference buildings which compare the bill of materials for structures constructed using standard clay bricks vs potential material substitutes such as hollow, lightweight, or autoclaved aerated concrete blocks. The results show that considerable reductions in material consumption can thereby be achieved for certain parts of the considered buildings. In the future, these effects should be incorporated in the MCIs as key variables for an MFA.

KEYWORDS
earthquake, FEM, MCI, MFA, substitutes

1 INTRODUCTION

1.1 Problem statement

The world’s growing population and increasing levels of prosperity are boosting demand for food and raw materials. In particular, we see an exploding demand in expanding cities for raw materials to construct new housing and infrastructure. Clearly, building materials are needed in very large quantities (in contrast to, eg, rare earth). Due to their burgeoning populations and the ongoing processes of urbanization, developing countries such as Bangladesh, India, Pakistan, and Afghanistan are facing a squeeze on raw materials for construction.

Raw materials are mostly extracted in the hinterland of large cities, where such (planned) mining activities often engender conflicts in land use.1-3 Stone and earth for the production of building materials are often extracted from sites previously used as farmland. Over the long term, such rededication of land can reduce the total supply of food for growing populations.2 Today, the standard clay brick is still widely used in construction. A common method to acquire clay for brick production is simply to extract this from the topsoil.1 Such removal of the topsoil, however, greatly impairs the general soil quality, threatening food security, and livelihoods in densely populated and rapidly urbanizing parts of South and Southeast Asia.4
1.2 The interdisciplinary knowledge gap

As described in Reference 5, geologists, environmental scientists, and regional planners are calling for appropriate political measures to stop the extraction of topsoil for brick production and instead to find alternative sources of raw materials. However, civil engineering studies on building materials tend to focus on particular mechanical properties, that is, ways of improving the strength, performance, and quality of the material, while less attention is paid to environmental aspects such as the crucial issue of the consumption and saving of materials.6–9 There is still a knowledge gap regarding greater efficiency in resource consumption while ensuring that building safety is not compromised from an engineering perspective.10 Yet it is precisely such knowledge that can form the basis for resource efficiency strategies to reduce conflicts in land use. Heavy raw materials such as gravel or sand are generally not transported over long distances but tend to be locally mined.11 Bimesmeier and Schiller12 as well as Schneider et al.3 highlight the need for an integrated view of the demand for construction materials, whereby questions of regional planning and the handling of raw material extraction can form part of the solution. As a basis for the development of appropriate planning instruments, European scholars are currently focusing on the development of material passports for buildings13 or a material cadastre for settlements.14 While developed countries are trying to address environmental issues with the help of such planning instruments or even green building certification systems, such initiatives have not yet gained a foothold in developing countries.

1.3 Material flow analysis as a tool to analyze resource-saving potentials

Regardless of the exact guidelines issued by governing bodies, it is clear that material savings in the construction sector will help to decouple (at least partially) the demand for raw materials from the demand for housing and infrastructure as well as to reduce the abovementioned fundamental conflicts of land use. In order to address this challenge as efficiently as possible, we require better knowledge of the material demand for buildings. Material flow analysis (MFA) is a suitable tool to describe material stocks and flows in the building sector for larger administrative units such as entire cities, for example, see References 15–18.

So-called bottom-up approaches give a detailed picture of the material composition of the building stock broken down into building types, reflecting the specific use and form of construction.19–26 The basic principle of MFA is to define indicators that describe characteristic material compositions of typical buildings as well as indicators to estimate the physical size of the building stock in relation to a certain reference quantity (practical measures of building size such as m² floor space); for example, see References 19 and 27. In the literature, such indicators are termed either material intensity (MI) or material composition indicators (MCI), for example, see Reference 28. They are a kind of density parameter, defined as material mass per reference value. The MI or MCI may refer to a cumulated material or may provide detailed information on several materials. The term MI is particularly well-established in top-down analyses, for example, see Reference 29 where the level of differentiation is commonly lower than in bottom-up analysis. The current author prefers the term MCI because this clearly indicates a “composition” of several individual materials. Mathematically, the MCIs are expressed as a single-column matrix, in which each (matrix) element represents a single material of the building or building element to which the coefficient “MCI” refers. For this reason, bottom-up approaches are also called coefficient-based approaches.15 The total mass of the material stock can then be calculated by multiplying the MCIs by the total sum of the respective stock (the reference quantity), for example, see Reference 30, 31.

1.4 Specifying MCI for various building types

MCIs describe specific material masses for building elements or entire buildings. A modular concept underlies the determination of MCIs for buildings,17 that is, by considering the material compositions of individual building elements such as the foundation, exterior wall, interior wall, ceiling, and roof of each building type. The material compositions MCIs(e) for a building element are then combined per building type to an MCI(b), which models the mass distribution of the different materials within the building, usually normalized to a reference quantity such as square meters of floor space. In this way, the influence of the building size on the quantity of material is factored out of the MCI. In the final determination of material masses, we take account of the building size by correctly multiplying the reference quantity.19

Determining the MCIs for building types is rather time-consuming, as it is usually performed step by step for each individual building element in each individual building type. In order to keep the necessary analysis steps and data volumes for MFA manageable for larger investigation areas, simplifications are indispensable when designing MCIs. Thus, there is exactly one fixed set of MCIs for each type of building. One simplification is, for example, to assume a quasi-linear relationship between the size of a building and its material mass to ignore engineering dependencies resulting from nonlinear material and structural behavior as well as location-dependent boundary conditions (e.g., the subsoil as it impacts earthquake resistance).5,32 This concerns, for example, the influence of the building height, which in this case is only indirectly influenced by the floor area as a reference quantity. As Schiller et al.33 pointed out, location-related contexts must therefore be taken into account when using MCI. The design of some building elements will also impact other elements via structural coupling—in other words, they are not independent parameters.

1.5 Research hypothesis and aims

This exploratory study aims to improve the determination of MCIs for bottom-up stock estimates. The research is based on the following
hypothesis: There exist dependencies between the individual components of a building. While the degree of dependency is as yet unknown and also varies from building to building, it will affect the efficiency of material substitution of a building element in relation to the resource consumption of the entire building (secondary effect). Here we understand efficiency as a major reduction in the total mass of material in the building, in this case the substitution of one material in one type of building element. In order to be able to use the bottom-up MFA concept based on MCIs to illuminate efficiency issues with regard to material substitution, it is necessary to consider the relationship between material composition and static load-bearing capacity on the two coupled scales of “building element” and “building.”

The outlined knowledge gap on the relationship between resource consumption and building safety from an engineering perspective formed the starting point for our study. The aim of the current paper is to close this gap by focusing on building materials that consume less resources than ordinary brick masonry in terms of the total mass. Specifically, we investigate some reference buildings in Pakistan, Afghanistan, and India to determine how the substitution of alternative materials for brick walls can impact resource consumption. The exemplary buildings are simulated models whose design is based on existing buildings. These were applied to a computational model that considered different seismic zones in the aforementioned countries to investigate the impact of these locations on the material requirements of various structural elements. The seismic zones are, for example, the cities of Gujranwala and Islamabad in Pakistan and Kabul in Afghanistan (see also Figure 1). The sub-study in India was carried out purely based on models using the various zone parameters. In particular, this preliminary study investigates those building elements which show significant interdependencies as well as aiming to identify which building elements or materials have the greatest potential for resource-saving and what the expected dimensions of these savings are.

2 | METHODOLOGY

2.1 | Building types and codes

2.1.1 | The trend toward reinforced concrete buildings

Within the process of global urbanization, we can observe the increased deployment of reinforced concrete in buildings, especially in the large cities considered here. This use of reinforced concrete rather than traditional construction materials can be attributed to the rising wealth of these countries, their burgeoning populations, and the high cost of land, which promotes taller and denser forms of construction. Currently, reinforced concrete buildings are most commonly found in urban areas, as confirmed by the World Housing Encyclopaedia (WHE) Report Database, which encompasses several housing reports from around the world. However, it is not unusual to see reinforced concrete structures in suburban areas, although in the majority of cases these are commercial buildings such as hotels, offices and shopping centers, and so forth. In large cities, reinforced concrete frame structures have become increasingly popular over the last two decades. This prevalence in the use of reinforced concrete can, among other factors, be attributed to the growing awareness of its strength in load-bearing structures compared to non-reinforced brick masonry, particularly in terms of earthquake resistance.

Most of the structures currently being built in India are reinforced concrete skeleton structures, consisting of a reinforced concrete frame and brick masonry as infill. This type of construction is widely preferred even though masonry buildings are much cheaper to erect. In major Pakistani cities such as Islamabad and Lahore, about 10% to 15% of buildings are constructed in reinforced concrete, of which the majority are commercial and public buildings such as hotels, offices, hospitals, educational institutions, and so forth. Such reinforced

![Percentage material savings for the reference buildings (HC: Hollow core concrete blocks, LC: Lightweight concrete blocks, AAC: Autoclaved aerated concrete blocks). Source: R. Ortlepp/IOER](image)
Concrete structures are generally low to medium height (three to eight stories) with a floor height of 3 to 3.35 m. While reinforced concrete buildings have been constructed in Pakistan for more than 25 years, for most of that time they made up a small share of the building stock. In recent years, however, the number of reinforced concrete buildings has rapidly increased, especially in the state capital and provincial capitals. Similarly, construction practices are changing in India, with many types of residential structures now built using reinforced concrete. In this way, the reinforced concrete frame is now the dominant structural design for new buildings in the rapidly growing cities of South and Southeast Asia.5,32

### 2.1.2 Construction standards and codes in the countries under investigation

Around the world, construction standards and codes dictate the dimensions that engineers must adapt to ensure that structures meet load-bearing requirements as well as sufficient serviceability and durability. Generally, such codes stipulate limit states for diverse structural parameters. The need to comply with such limits has a direct impact on the material requirements of buildings, thereby setting an upper boundary on material savings. Serviceability limit states (SLS) are mostly stress-related deformations or deflections of a structure that should not be exceeded to avoid possible damage (e.g., cracking) to structural components such as ceilings, floors, partition walls, installations, and so forth. It is also important to meet the requirements for usability (deflections, vibrations) and to ensure the well-being and comfort of users. However, the ultimate limit states (ULS) have the highest priority in design because they are intended to avert danger to human life and limb. When ULS are exceeded, a building is in danger of collapse or of suffering some form of major failure due to a loss of equilibrium throughout the structure or in individual structural components, a loss of stability (especially in slender components), or the occurrence of failure mechanisms in the entire system or individual structural components. The definition of ULS is rooted in a comprehensive safety concept as defined in the applicable building code of a country or region, such as EN199035 in Europe.

Construction design in Pakistan generally obeys the Building Code of Pakistan (BCP),36 supplemented by the American Concrete Institute’s ACI 318 Building Code,37 which mainly contains design rules for steel reinforcement. The specification of ultimate and serviceability limit states is in accordance with BCP.26 The Uniform Building Code UBC 9728 is still used for earthquake design in Pakistan, although formally it has been replaced by the International Building Code (IBC) of 2006.39 The designation of seismic zones is also regulated by the BCP,26 which, for example, determines that Gujranwala is in seismic zone 2A and the country’s capital city of Islamabad in seismic zone 2B.

As Afghanistan has no building standards of its own, the internationally recognized American codes are usually applied in the country’s construction sector.32 The standard design procedure is based on the uniform building code28/international building code,39,40 the American Concrete Institute’s ACI 318-08,37 or the American Society of Civil Engineers’ ASCE 7.42 While northern Afghanistan lies on the stable Eurasian tectonic plate (earthquake zones I and II), to the east, south, and west, the country is surrounded by active plate boundaries that cause deformations and destructive earthquake zones (III and IV).32 The capital Kabul—also by far the largest city with over 4 million inhabitants—is located in earthquake zone III.

India maintains its own national building code, published by the Bureau of Indian Standards (BIS). These Indian construction standards42–48 provide all the necessary information on materials, analysis criteria, design parameters, reinforcement details, and loading for all types of reinforced concrete structures, including information on diverse combinations of loads. Like Afghanistan, India is also highly earthquake-prone. The latest version of the country’s seismic zone map, which is included in the earthquake-proof design code of India,45 designates four zones of seismic activity (II-V). The associated stipulations for the load-bearing capacity of buildings thus also impose limits on potential reductions in building materials.

### 2.2 Preliminary study of reference buildings

In order to get an overview of the likely impact on the material requirements of typical buildings when traditional brick masonry is replaced by other materials, a series of (modeled) structurally robust reference buildings was calculated. For each building design, we created a finite element model (FEM model) of the load-bearing structure with the requisite dimensions. The clay bricks frequently used in practice to infill the reinforced concrete frame were then replaced in the models by other lightweight materials such as autoclaved aerated concrete (AAC) blocks or lightweight concrete (LC) blocks. Subsequently, we recalculated the dimensions of the new load-bearing structure, taking into account the changed dead loads. The weights of the material substitutes are given in Table 1.

The information here refers to the building materials as end products. Of course, the discussion could be further refined and broken down to reflect the individual raw materials, that is, cement, gravel, sand, and water in the case of LC; cement, sand, aluminum, and water in the case of AAC. However, we have no details of the relative quantities of raw materials used in the investigated products. Indeed, only a handful of studies have attempted to estimate the raw material composition of end products; for example, Reference 49 describes a methodology for this, and detailed data can be found in Reference 50. In this current study, however, we are not aiming at this level of detail, since the resulting weights of the end products are the sole factor impacting the dimensioning of the structure.

From the FEM simulations and, if necessary, optimization of the building element geometries, the resulting material demands for the examined construction variants can be analyzed and quantified for each building element and building material. This reveals noticeable discrepancies, allowing conclusions to be drawn about possible interactions. Here we aim to pinpoint significant dependencies between different types of construction elements as well as to identify types of
construction elements and materials which offer the greatest potential for resource-saving. Table 1 gives an overview of the reference buildings.

The reference building #1 in Pakistan is a college for girls. Typical for such buildings in Pakistan, it features a frame construction. Concrete designs are increasingly popular in Pakistan: Almost 50% of taller buildings (four floors or more) are now built of concrete. The footprint of the college is 1180 m². There are four floors, each of height 3.7 m. The building has three munties (staircase towers/covers on the roof), two in the stairwell and one munt in the library, each 3.5 m high. The foundation is located 3.05 m below the first floor. In line with the bearing capacity of the ground, this was designed as a mat foundation. All walls are made of clay bricks of standard size for Pakistan, namely L × B × H = 22.86 cm × 11.43 cm × 7.62 cm. Exterior clay brick walls are 34.29 cm thick, while interior walls have a width of either 11.43 cm or 7.62 cm.

The reference building #2 is an office block in Pakistan with a footprint of 627 m². The building has three floors of height 2.85 m each; the foundation is 1 m deep. Each office has a different floor plan. All walls are clay brick masonry, except for the glass walls at the front of the building. The thicknesses of the clay brick walls are similar to building #1. The reinforced concrete shear walls have a thickness of 25 cm.

The reference building #3 is an apartment block in Kabul, Afghanistan. This reinforced concrete structure comprising a foundation, column, beam, shear wall, staircase, and slab is designed to withstand the climatic conditions and local seismic risk (earthquake zone III). The building has six upper floors and a basement. All floors are divided into apartments. The underground basement, which serves as storage space, has a height of 3 m. The building has a flat roof. Each storey has a height of 2.88 m (floor to floor). The clay brick walls are 35 cm thick, which are substituted in this study by AAC block masonry walls of thickness 22.5 cm.

The load-bearing structural elements such as columns, beams, slabs, shear walls, and foundations of the above-mentioned reference buildings were modeled in an FEM computer simulation with all other building materials recorded as dead loads on the load-bearing structure. These include stairs, glass façades, windows, doors, munty, floor and roof structures as well as foundation, mortar, tiles, wall plaster, skirting boards, and so forth (hereinafter referred to as finishing). With the help of the FEM simulation, the dimensions of the supporting structure could be calculated for different loads, that is, when the clay brick walls are substituted by lighter materials. In addition to the load-bearing reinforced concrete structure and the non-load-bearing masonry infill, the non-load-bearing materials (finishing) were also analyzed in this study with regard to material composition. This allows for a more realistic determination of MCI than if merely the supporting structure is considered, as was the case in Reference 5.

For the purpose of comparison, we refer to the results of this earlier parameter study on the influence of material substitutes for Indian residential apartment buildings with different storey heights (reference buildings #4-6); for a detailed description of the construction, please refer to Reference 5. In our discussion below, we provide these findings for the reference buildings #1 to 3.

3 | RESULTS

3.1 | Material quantities of reference buildings

Table 2 shows the masses of the various reference buildings as derived from the FEM simulations. Here we compare traditional clay brick (CB) masonry as infill with lightweight substitutes. In detail, the table gives the weights of the various structural elements of the reinforced concrete load-bearing structure and the masonry infill walls (excluding finishing). We also distinguish between the parts of the building that are located above and below ground. It can be seen that, depending on its type, the foundation in some cases represents a significant fraction of the total mass of the reference building (between 7% and 35%). In the case of a mat foundation, the relative share of the weight of the foundation to the total mass is on average about 10% higher (16%-35%) than the isolated foundation (7%-24%).

The superstructure of the reference buildings #1 to 3 was broken down into the constituent structural elements, namely columns, vertical supports, horizontal supports, and slabs. These structural elements are further divided into load-bearing elements and non-load-bearing elements (i.e., finishing materials such as glass, doors, windows, and so forth). The mass of each structural element is calculated based on the dimensions provided in Table 1 and the material properties given in Table 2. The results are then aggregated to obtain the total mass of the superstructure for each building.

Table 2: Material quantities of reference buildings

| Building #  | Footprint (m²) | Foundation Type | Substitute Material | Total Mass (kN) |
|------------|---------------|-----------------|---------------------|----------------|
| #1         | 1118          | MAT foundation  | Hollow concrete (HC) blocks, weight 10 kN/m³ | 1650           |
| #2         | 627           | Isolated foundation | Lightweight concrete (LC) blocks, weight 9.8 kN/m³ | 1200           |
| #3         | 580           | MAT foundation  | Autoclaved aerated concrete (AAC) blocks, weight 5.5 kN/m³ | 1400           |
| #4-6       | 180, 384, 900 | Isolated foundation | Autoclaved aerated concrete (AAC) blocks, weight 7 kN/m³ | 1600           |

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## Table 2
Compilation and comparison of the material quantities of infill walls and the load-bearing structure depending on the infill wall material [t]

| Reference building | Infill wall material | #1 CB | #1 HC | #2 CB | #2 LC | #3 CB | #3 AAC | #4 CB | #4 AAC | #5 CB | #5 AAC | #6 CB | #6 AAC |
|-------------------|----------------------|-------|-------|-------|-------|-------|--------|-------|--------|-------|--------|-------|--------|
| Masonry           | Clay bricks          | 3009.9| 1443.9| 444.8 | 201.5 | 1199.4| 252.2  | 88.0  | 30.8   | 180.0 | 454.0  | 63.0  | 158.9  |
|                   | Substitute           | –     | 1443.9| –     | 201.5 | –     | 252.2  | –     | 30.8   | 63.0  | 158.9  | –     | –      |
| Concrete          |                      | 6173.9| 6019.7| 1600.7| 1427.1| 2833.8| 2833.8 | 232.5 | 969.8  | 4219.9| 4133.4 | –     | –      |
| Foundation (below ground) |                  | 2760.3| 2606.6| 488.6 | 340.9 | 621.2 | 621.2  | 52.8  | 40.2   | 99.1  | 393.5  | 289.0 |
| Superstructure (above ground) |                  | 3413.6| 3413.1| 1112.1| 1086.2| 2212.6| 2212.6 | 191.0 | 847.3  | 849.3 | 3826.4 | 3844.4|
| Slabs             |                      | 2106.7| 2106.1| 635.7 | 635.7 | 911.1 | 1130.0 | 1301.5| 345.5  | 1446.5| 1464.5 | 79.3  |
| Frame             |                      | 1306.9| 1307.0| 476.4 | 450.5 | 1301.5| 1301.5 | 79.3  | 345.5  | 1446.5| 1464.5 | 79.3  |
| Columns           |                      | 615.3 | 615.5 | 52.5  | 43.7  | 486.7 | 486.7  | –     | –      | –     | –      | –     | –      |
| Beams             |                      | 691.5 | 691.5 | 176.3 | 159.2 | 841.8 | 841.8  | –     | –      | –     | –      | –     | –      |
| Shear walls       |                      | –     | –     | –     | –     | –     | –      | –     | –      | –     | –      | –     | –      |

### Steel

| Foundation (below ground) |                  | 65.2  | 55.9  | 17.4  | 14.9  | 15.2  | 13.9   | 0.5   | 0.4   | 1.2   | 0.9   | 21.5  | 11.0  |
| Superstructure (above ground) |                  | 118.0 | 102.0 | 33.5  | 33.0  | 43.3  | 40.9   | 6.5   | 5.2   | 23.0  | 21.0  | 123.6 | 105.6 |
| Slabs              |                      | 48.7  | 38.3  | 13.6  | 13.7  | 14.0  | 12.8   | 2.0   | 2.0   | 11.0  | 11.0  | 57.6  | 57.6  |
| Frame              |                      | 69.3  | 63.7  | 19.9  | 19.3  | 29.3  | 28.1   | 4.5   | 3.2   | 12.0  | 10.0  | 66.0  | 48.0  |
| Columns            |                      | 21.7  | 29.4  | 0.9   | 0.9   | 14.0  | 13.6   | –     | –     | –     | –     | –     | –     |
| Beams              |                      | 37.6  | 34.4  | 14.6  | 14.0  | 15.3  | 14.5   | –     | –     | –     | –     | –     | –     |

### Total material

|                  | 9366.9 | 7621.5 | 2096.4 | 1676.5 | 4091.7 | 3140.8 | 338.8 | 268.8 | 1174.0 | 1033.3 | 4819.0 | 4408.9 |

Abbreviations: AAC, autoclaved aerated concrete blocks; CB, clay bricks; HC, hollow core concrete blocks; LC, lightweight concrete blocks; Bold = cumulative values for the materials (across all structural elements); Italic = differentiated values for the individual components of the frame (where available).

### Figure 2
Percentage material savings for individual building elements and material.

Source: R. Ortlepp/IOER
beams, shear walls, and slabs, to get a clear picture of how replacing the clay brick masonry affects each element. However, only aggregate values for the frame are available for buildings #4 to #6 from the Indian study. For the purposes of comparison (see also paragraph 3.2, Figures 1 and 2), the data for the individual frame components for buildings #1 to #3 (Table 2, in italics) were also combined into one indicator “frame,” consisting of columns, beams, and shear walls.

In addition, a detailed analysis of the individual material masses for finishing was conducted on the first two reference buildings in Pakistan (#1 and #2). Typical finishing materials employed in the ground floor, walls, façade, windows, doors, stairs, floors, and roof are, for example, cement mortar, gravel, sand, glass, aluminum, plywood, ceramic tiles, red clay tiles, bitumen, and mud for insulation. While the detailed analyses are necessary to ensure that the MCIs are determined as accurately as possible, these finishing materials are not affected by the substitution of the infill wall material. For this reason, we merely provide data on the total mass of finishing rather than the individual material masses. This total mass of finishing is relevant for calculating the final mass of the building (of which it constitutes around 20%-25%). In the examined cases, the total mass of the finishing is 1650 t for building #1 and 680 t for building #2. This confirms the relevance of this factor in assessing the potential material reduction for the entire building.

3.2 | A material reduction in reference buildings due to wall material substitution

In all the reference buildings, we see a significant reduction in mass due to material substitution. Specifically, by replacing standard bricks with lightweight materials as wall infill, the total mass of consumed materials can be reduced by ~20% in most cases (#1 to #4) (Table 3). Only buildings #5 and #6 show a much smaller potential for material savings. The largest share of reduced material quantities can be attributed to the substituted masonry itself (primary effect) rather than to redesigned structural elements. This lower weight, due to the reduced density of the substitute materials, can be between 50% and 80% of the initial mass of the clay brick wall.

Nonetheless, clear secondary effects can also be detected, namely when the reduced mass of the wall material permits a less robust reinforced concrete load-bearing structure. Except for reference building #2, these effects are most evident in the amount of steel reinforcement, with potential savings of up to 20%, along with a smaller reduction in the use of concrete ranging from 2% to 5%. The fact that this situation is reversed in reference building #2 can be explained by an optimization of the geometries of the reinforced concrete structural elements, leading to an ~10% reduction in the use of concrete. As a result, these components are more highly stressed, preventing the large reductions in reinforcement steel seen in the other reference buildings. In this way, we see that the reduction in the consumption of both concrete and steel can be significantly influenced by the structural design. Clever design solutions can reduce the amount of concrete by more than 10% if, for example, the LC blocks used in reference building #2 are replaced by AAC blocks (with about half the weight). Such AAC blocks were investigated in reference building #3, although here the design goal was to reduce steel without changing the dimensions of the RC structural elements.

For a more detailed assessment of potential material savings, it is necessary to consider the effects of material substitution on the various structural elements and, in particular, on the individual materials contained therein. Figure 1 shows the percentage material reduction for the six reference buildings broken down into the materials hollow, lightweight, or aerated concrete masonry as well as concrete and reinforcing steel in the structural element groups: frame, slabs, and foundation. Figure 2 gives the same results clustered by material and structural element groups. While the data presented in Table 3 refers to the entire building, the percentages shown in Figure 1 and in Figure 2 relate to the individual structural elements. Regarding these individual elements, the percentage savings in the material can appear significantly greater than the total savings for an entire building. In the latter case, of course, the proportional changes will average out when the total mass of the respective material is calculated for an entire building, as can be seen in regard to steel in reference building #6.

It can be clearly seen that the largest share of material savings in all buildings is due to substituted masonry. In fact, no FEM simulation is required to calculate this primary effect because the reduction correlates directly with the difference in density between clay brick and the material substitutes HC, LC, and AAC.

The secondary effects in the load-bearing reinforced concrete elements, on the other hand, are determined by optimizing the modeled structural design after reducing the dead loads to reflect the substitution of clay brick masonry. Here we see significant differences between the load-bearing structural elements of the superstructure and the foundations below ground. Regarding the former, a distinction can be made between the impact on concrete and on reinforcing steel as well as between the frame and slabs. A reduction in concrete in the frame structure (including columns, beams, and shear walls) was only identified in reference building #2, where the dimensions of the columns and beams were downsized due to the reduced wall load, leading to a material saving of 5%. In this case, the largest mass of concrete is contained in the shear walls (see Table 2). Looking more

| Reference building | #1 | #2 | #3 | #4 | #5 | #6 |
|--------------------|----|----|----|----|----|----|
| Masonry            | −52% | −55% | −79% | −65% | −65% | −65% |
| Concrete           | −2% | −11% | 0% | −5% | −2% | −2% |
| Steel              | −14% | −6% | −6% | −21% | −10% | −20% |
| Total              | −19% | −20% | −23% | −21% | −12% | −9% |
closely at the data, we see a 17% drop in the mass of concrete within the columns and 10% within the beams. The slabs, on the other hand, are unaffected by the wall material substitution; there are no secondary effects in lower concrete consumption because the slab geometry in all the models remains unchanged.

In the case of reinforcing steel, we find a different situation. Here, clear secondary effects can be seen in all types of structural elements. A reduction in the demand for reinforcing steel in buildings #1 and #3 was calculated at about 20% and 10%, respectively. This can be attributed to the fact that the loads on the partition walls standing on these slabs are significantly reduced by the substitution of clay bricks, permitting a reduction in the level of steel reinforcement while maintaining the same stress level. In the other buildings, all partition walls are directly supported by beams and therefore have no effect on the slabs. Steel reductions were also observed in the frames of all reference buildings. This reduction was the smallest (only 3% for the beams alone) in building #2 because here the optimized (concrete) element dimensions increase the level of stress on the structural elements. The proportional savings in the other reference buildings vary considerably from 4% to 29%, so that no generally valid statement can be made on the specific reduction in mass. In general, the proportion of reduced mass is roughly the same in beams and columns, as indicated by the data for reference building #1 and #3 (cf. Table 2).

Although architects and engineers focus most of their attention on the superstructure, by far the greatest savings potential can be attributed to the foundation, which is usually rather neglected in this context. Here we carried out a comprehensive optimization of the foundation geometries of all buildings. This revealed potential savings in concrete ranging between 20% and 30%. The potential reduction in reinforcing steel within the foundations is also clearly apparent in all reference buildings, although there is considerable variation here between the reference buildings regarding the relative mass.

4 | CONCLUSIONS AND OUTLOOK

Our initial hypothesis of dependencies between the individual structural elements of a building has been confirmed by the results of the exploratory study. In particular, the investigation of the six reference buildings showed that the material substitution of clay brick walls by lightweight cementitious materials has a twofold impact on demand for resources: on the one hand, there is a clear primary effect due to the wall material substitution itself and, on the other hand, we see significant secondary effects in the reinforced concrete load-bearing structure.

With a focus on land use, the repercussions of this primary effect are rather complex. Alongside a reduction in the consumption of materials, we also find, in the case of substituted materials, a shift in the sourcing of raw materials. In particular, rather than using topsoil to produce clay bricks, manufacturers can turn to raw materials such as cement, gravel, and sand (e.g., from riverbeds) to produce lightweight cementitious building materials such as hollow, lightweight, or aerated concrete. While this shift may reduce the potential for conflicts with farmers, for example, it may at the same time foment conflict elsewhere, even if the total material mass of the substitute material is lower than for bricks. Furthermore, different materials are associated with different levels of GHG emissions. The quantities of gases are largely dependent on the manufacturing process. In developing countries, in particular, emissions are often high due to the use of antiquated technologies, especially in brick production. Therefore, in addition to the impact on land use, material substitution can also help reduce GHG emissions. Here various environmental considerations may lead to trade-offs; any decision on which materials to use cannot be made strictly on the basis of potential reductions in material mass. Rather, this discussion must always take account of local factors such as typical forms of land use, the supply and demand of materials as well as GHG emissions.

In addition, we have clearly shown that material substitution has a secondary impact on other structural elements of the load-bearing structure. The level of material reduction achievable in the individual structural elements of the RC frame varies substantially between the reference buildings and depends on different influencing factors. A generally valid statement on the degree of dependency cannot be drawn from the current preliminary study due to the considerable variation in the calculated results in some cases.

However, we can identify many significant dependencies that suggest ways to further refine MCIs as used in bottom-up MFA: The greatest potential mass reduction is generally offered by the foundation, where savings of 25% to 33% in concrete and steel reinforcement are feasible. Another significant dependency was found in regard to steel reinforcement in the columns and beams of the frame. A further possible dependency may be in regard to the mass of concrete used to construct the frame. While this is indicated by the results for building #2, further investigations are required to determine whether this can be formulated as a general statement. The difficulty here is that, depending on the optimization goal of the planning engineer, the focus of any reduction in material consumption can tend more towards concrete or steel reinforcement. On the other hand, this will also depend on the above-mentioned context of local land use or the boundary conditions of supply and demand.

In the case of reference building #2, we note the strong secondary effects that can be achieved by an intelligent optimization of the load-bearing RC structure. Here a total of 420 tons of material could be saved through substitution, namely 243 tons of masonry and 177 tons within the RC structure. This means that the material savings through the reduced mass of masonry could be increased by a factor of 1.7 through optimization of the load-bearing structure. Considering the fact that the maximum weight reduction of masonry material was not applied for reference building #2, a 1:1 ratio between the primary and secondary effect in material savings could conceivably be achieved in the future. This means that the same amount of material could be saved in the load-bearing RC structure as by substituting the masonry itself.

The current definition of MCI does not yet allow for these secondary effects. One idea for the future development of MCI is to define and model certain MCI(e)s (i.e., related to building elements)
as coupled parameters. For the issue of material substitution, this mainly concerns MCI(s) where the loads have to be transferred from one component to another. The MCI(s) related to the foundation show the greatest level of dependency. To be more precise, the MCI of the load-bearing elements located lower down are forced to adapt to changes, that is, substitution of materials, in building elements located higher up. It may also be possible to simply define some sort of mitigation factors for these MCIs in more comprehensive future parameter studies. With more accurate MCIs, it should be possible to perform more sophisticated analyses in the context of bottom-up MFA.

If we consider the impact of material savings on regions rather than individual buildings, the author believes that the greatest resource-saving effect can be achieved by identifying those parts of the building where the secondary effects are the highest, that is, where small initial changes have a large impact on the mass. This concerns above all the foundations, which should be the focus of resource efficiency measures. Although architecturally of little interest, these structural elements are highly significant due to the considerable potential for material savings. In a nutshell, we find the greatest effect where nobody can see it—hidden below ground.

Bottom-up MFA based on MCIs is an appropriate tool to facilitate discussion of efficiency issues related to material substitution. However, it is necessary to consider the relationship between material composition and static load-bearing capacity on the combined levels of individual structural elements and entire buildings. This preliminary study has revealed some parameter dependencies between structural elements, which will require more attention in the future. These relate largely to the frame construction and, most importantly, to the foundations. Here we are dealing with a chain of interdependencies, that is, the type of optimization in the frame will in turn affect the loading of the foundations. One major challenge for the future will be to generalize and simplify the MCI approach while retaining the essential dependencies that have been identified in regard to mass.

**DATA AVAILABILITY STATEMENT**

Data are available on request from the author.

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