Environmental and Economic Tradeoffs in Building Materials Production in India

By

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Abstract

The current and projected growth of India's economy and population will continue to lead to increased demand for buildings and infrastructure, and there is a real need to consider what this increase means in terms of natural resource depletion, air pollution, contributions to global warming through greenhouse gas emissions during production and transport, and energy demands to be placed on an already strained energy network. Fired-clay bricks are the most commonly used building material in India, but recently, masonry units that don't require firing (stabilized bricks) have penetrated the market. There has been an exploration of the amalgamation of traditional earthen building materials combined with chemical binders. While these masonry materials are often considered superior in terms of environmental impact due to their lack of firing in visceral, black smoke-producing kilns, as well as their typically local (even on-site) production, there has been limited research into their actual environmental footprint.

This thesis establishes models for robust analysis, and analyzes the environmental and cost tradeoffs associated with various building materials' choices to evaluate the hypothesis that the optimal materials choice is heavily dependent on the local soil composition and industrial ecosystem. That is, there is likely not one answer to the question of which is better: traditional fired clay bricks (red bricks) or alternative, cementitious materials, and instead, decision making must be assisted by analysis of the overall environmental impact of the upstream production and transportation of each material. Because of the variety of conditions throughout India, there is a need for this sort of tool to perform these analyses to determine the conditions under which different building materials have better environmental and/or economic outcomes. The analyses performed in this thesis conclude that there is the potential for alternative materials to break into the market, particularly in areas where red bricks are not produced on an industrial scale.

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1 INTRODUCTION

India is currently the second most populated country, with its 1.2 billion inhabitants accounting for 17.2% of the world's population (World Bank). The World Bank projects the Indian population growth rate to be 1.41%, which means that India could have a population of 1.5 billion by 2030, making it the world's most populated nation. Along with a growing population, India is experiencing a growing GDP, with conservative projections assuming an 8% annual growth until 2018 and a 7% annual growth until 2030 (MGI, 2010). Given the rise in population and GDP, rapid development of infrastructure and the built environment is both crucial and inevitable, with an estimated 700 to 900 million square meters of commercial and residential space needed to be built each year until 2030: an area equal to a new Chicago every year (MGI).

Housing construction will be needed to accommodate the growing population, but there are also two more factors to consider: First, 50% of the current population is below 25 years old, and 65% is below 35 years old. This disproportionate number of young people in the population increases the overall need for housing in the immediate future. Furthermore, India is plagued by poverty, as can be seen by a casual drive in almost any city or rural area throughout the country. In 2001, 15% of the entire population lived in urban slums, which are, perhaps, the most visceral examples of poverty. However, poverty is not limited to the slums, and data from 2004-2005 shows that 26% of the entire population was living below the poverty line. A task force established by the government in 2008 points out that in 2006-2007, the real estate sector accounted for 4.5% of the GDP and 7% of the urban work force, positing that alleviating the housing shortage would also raise the GDP by at least 1-1.5% (Parekh et al, 2008).

The task force found that 99% of the housing shortage pertains to the economically weaker section (EWS) and the lower income group (LIG). Similarly a recent study by the McKinsey Global Institute (MGI) found that, in general, health, education, and housing were the three most pressing, unmet needs for the vulnerable in both urban and rural settings (MGI, 2014). MGI also noted that it is likely that many urban Indians fall into the vulnerable category with affordable housing an unmet need. The task force, in fact, found that 35% of urban families live in 1 room dwellings, with 65% of these households being comprised of at least 4 members, demonstrating that better housing is a current as well as a future need for India.

This pressure to develop the built environment inevitably puts pressure on the natural environment through resource exhaustion, arable land-use, and increases in industrial air pollution. Buildings are reported to consume 40% of the world's energy, while their construction accounts for 40% of raw stone, gravel, and sand use, 24% of virgin wood use, and 16% of water use(Dixit et al, 2010). In India, the construction sector is responsible for 22% of CO_2 emissions (Reddy et al, 2003), and housing accounts for 60% of the total materials' consumption by the construction sector (Chani et al, 2003). As attention has turned to different industries to reduce global energy usage and GHG emissions, the UN Environment Program has proposed that the "building sector has the largest potential for delivering long-term significant and cost-effective GHG emissions" reductions (UNEP).

In general, life cycle assessment (LCA) is an accepted technique for estimating environmental impact of a product, and it has been increasingly applied to buildings (Ghattas et al, 2013). LCAs look at the entire lifetime of a product—from cradle-to-grave—to calculate materials required, energy consumed, emissions produced, and overall impact. ISO 14040-2006 standards for LCA define the terms of LCA and describe the framework for LCA study: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation. The ISO 14044 standards provide further detail regarding LCA methodology. LCAs can provide information about different components and environmental outcomes. Building LCAs (and essentially all LCAs) can be incredibly resource intensive, requiring extensive data collection and modeling for each phase of a building's lifetime.

An oft under-investigated driver of the environmental impact of buildings is the production of building materials themselves. The impacts from the production of building materials is accounted for in LCA and is sometimes referred to as the embodied phase. In India, fired clay bricks (henceforth referred to as red bricks)(including bricks that include waste materials like fly ash) are estimated to account for 92% of the masonry units produced per annum (Maithel et al, 2011). Production of these bricks uses traditional firing technologies and locally available clay that is typically excavated manually. However, there has been a surge in research activities to develop and introduce alternative masonry materials into the market. Nevertheless, little research has been produced to analyze the comparative environmental (and economic) costs associated with these materials and different production processes. An often touted alternative to fired

bricks are concrete stabilized earth blocks (CSEBs), which are composed of compressed soil with a small amount 5-10% of a stabilizer (cement or lime). These materials are assumed to be environmentally preferable to red bricks because they do not require firing; even though stabilizer is produced in an energy intensive process, the use of such a small amount is considered a better alternative to firing the entire masonry unit. Given the pressing need for new development throughout India, tools must be built to quickly grasp the benefits or disadvantages of various materials or production choices. Such impacts hinge on characteristics such as locally available materials (and soil composition), fuel use, energy demand, and transportation distance of components that otherwise need to be imported.

Assessment of the environmental and economic impacts of building materials production can therefore have real consequences on the immediate future of the Indian landscape, as materials choices (or research into new materials or production methods) can either be supported or discouraged. Interviews with Indian entrepreneurs have stressed the importance of meeting a price point for alternative materials that is only marginally less than the selling price of red bricks. Materials that are priced too low have the potential of suffering the "Nano effect:" The Tata Nano was first marketed in 2009 as the world's cheapest car, but as it turns out, no one wants to be seen driving the world's cheapest car. Regardless of a person's place on the economic ladder, there exist similar image issues, and a car that does not satisfy aspirations will not sell. The Tata Nano is currently being rebranded to overcome this marketing pitfall, including price increases (Able, 2014). The purpose of this anecdote is to point out the importance of aspirations. Home ownership, in particular, is valued very highly in India, and individual home owners will likely not want a material that is perceived to be "low cost." This is why achieving a similar price point to the materials currently used will be so important.

This thesis aims to analyze the impact of masonry unit production from a holistic perspective, determining the factors that drive environmental and economic impacts of masonry materials and analyzing the tradeoffs between different materials in different locations in India.

2 LITERATURE REVIEW

Throughout the past few decades, there has been an increase in activity researching the life cycle environmental impact of buildings. Traditionally, these studies focused on the operational phase of the building, but there has also been a shift to understand the production of building materials and construction of buildings themselves (the embodied phase). Described below are sources that describe the state-of-the-art in building LCA, the increasing focus on the embodied phase, and the state of this research in the Indian context, and the sources of uncertainty and variation in data and outcome that can affect these studies.

2.1 Building LCAs

LCA was originally applied to stand-alone products, and while the extension to buildings is a logical next step, there are a number of factors to consider (Dixit, 2012). LCA of buildings is not straight forward, as buildings are complex systems. First, the inventory data for buildings is hard to track because the number of components forming the building is large. Second, buildings have long life spans that are difficult to anticipate. Finally, buildings are dynamic: They are remodeled, maintained, and even expanded throughout their lifetime. Studies that performed building LCAs have found operational energy to be, on average, the main driver of a building's life cycle energy. Thus the traditional focus for the reduction of a building's energy usage has been in its operation. The following literature sources discuss the complexity of building LCAs, the need for increased focus on the embodied phase, the conclusions that can be drawn from existing studies, and the future direction for the field.

A recent report by MIT's Concrete Sustainability Hub (CSH) (2013) looked at 23 different studies that used LCA to analyze energy consumption and CO_2 emissions of residential buildings, noting that while most studies focused on these two factors, LCA is a tool that can be used for measurement of other components, such as water usage. The purpose of this report was to analyze differences in the scope of each of the studies. The report found that there were differences in functional unit definition, the lifetime of the building studied, and the system boundaries. In general, operation of a building constituted the major environmental impact of a building's life cycle. However, some of the studies showed that the energy impact of the

materials used could be equivalent to 30 years of energy use in a home (Verbeeck and Hens, 2010; Gustavsson and Joelsson, 2010). Furthermore, there were two additional studies left out of the analysis because they were not compatible that found the embodied phase could actually account for up to 50% of the lifecycle energy of a residential building. The report stresses that as building codes become increasingly stringent there will be more of a need to look at the embodied phase of buildings to decrease the overall lifecycle impact.

A 2014 article (Karimpour, 2014) reanalyzes 24 residential buildings from 10 previous studies across different climates (internationally) and finds that embodied energy can be actually 25% of a building's energy, concluding that in a carbon constrained economy it will become increasingly important to consider the embodied phase to reduce the overall lifecycle impact of buildings.

A literature review by Dixit et al (2010) provides a detailed analysis of parameters that drive embodied energy that would enable consistent and comparable data sources. Embodied energy is defined as the energy required for raw material extraction, transport, manufacture, construction, maintenance, disassembly, and decomposition. However, the current literature demonstrates a disagreement over what exactly the system boundaries for embodied energy are. Despite the definition of embodied energy to include the end-of-life phase, the authors describe embodied energy as being expended once in during the initial construction of a building, demonstrating the relative importance of building fabrication over deconstruction. Thus the greatest potential to reduce embodied energy is in the use of low energy intensive materials.

The article looks at various embodied energy figures published for commercial and residential buildings. It finds the average residential building embodied energy is 5.506 GJ/m^2 and the standard deviation is 1.56 GJ/m^2. In commercial buildings the average embodied energy is 9.19 GJ/m^2 and the standard deviation is 5.4 GJ/m^2. The variability in commercial buildings is greater than in residential buildings, but it is substantial in both, and the literature suggests that there is no standardized methodology to estimate the energy of building materials, leading to inconsistent results across studies.

The ten parameters that influence the variability across embodied energy analyses are: system boundaries, method of embodied energy analysis, primary versus secondary energy (energy

required for manufacturing the finished product versus energy used further upstream), geographic location, age of data, data source, completeness of data, manufacturing technology, feedstock energy consideration, and temporal representation. System boundary definition and method of embodied energy analysis are discussed below:

System Boundary

System boundary entails all of the components that factor into the analysis of the embodied energy or carbon analysis of a material. For instance, system boundary will include the materials and products used in the construction of a house, but could also include the transport of the materials to the site, the generation of waste materials, the transport of the waste materials for reuse or disposal, the processing of waste materials, and even the construction of the road network used for any of the transport.

Consistency in system boundary is important to consider when comparing different analyses, as some past studies were found to truncate the system boundary when the necessary data became difficult or too resource intensive to acquire (Dixit). These truncations are not consistent across studies, making it difficult to draw conclusions from different cases (Monahan and Powell, 2011). Furthermore, in addition to lack of data, these truncations occur due to value judgments by study authors in determination of the greatest drivers of the eventual results. Interestingly, Monahan and Powell point out that there is a consistent range of embodied energy and carbon results found in the literature.

Hammond and Jones discuss the development of an open-access database for embodied energy and carbon for the construction industry in The United Kingdom (2008), citing the system boundary differences as a key driver of differences among the aggregated data points, including geographic origin in their definition of boundary. The authors depend on industry professionals' input to direct the choice of "best values" for inclusion in the database.

Method of embodied energy analysis

Process-based analysis is the most common and the most accurate, and it begins with the product in question and then works backward to account for the production processes (Monahan and

Powell). One complication that often arises in process-based analysis is the truncation of system boundaries as discussed above. (Dixit; Treloar, 1997). Monahan and Powell caution that the results from these types of studies should be used tentatively and as indicators because they are dependent on the individual scenario studied, and may not be universally applicable across studies.

On the other hand, input/output (IO)-based analysis looks at national economic IO data tables. An IO table shoes the flows of goods and services across different sectors of an economy and coefficients are used to translate these values to energy consumption values. These values can then be translated to carbon emission values based on coefficients that are dependent on the type of energy, the energy mix, etc. This method is considered to be nearly complete as it better accounts for the entire value chain, but is less accurate because it looks at data in aggregate and the error in the results can range up to 50% (Dixit). Assumptions that affect the accuracy of the results from this method are proportionality assumptions, homogeneity assumptions, and the assumption that price is an accurate indicator of the actual exchange of goods and services (Treloar). As mentioned previously, the pure form of this method is not typically used, but IO data is applied in methods that hybridize process-based and IO-based analyses.

The most common form of hybrid analysis is process-based hybrid analysis (Dixit). In this method, the inventory of physical materials collected by a process-based analysis is combined with the energy intensities derived by IO-analysis. This method has similar issues with system boundary as seen in pure process-based analyses. The key difference is that the application of IO data renders the system boundaries of basic input materials complete (Treloar). Still, the inputs of materials that require complex assembly are often neglected, and it was found that the number of materials analyzed in completed buildings using this method is typically less than 50 (Treloar).

Additionally, to have the two sets of data in terms of the same units, the energies derived from the IO tables are translated to physical units by multiplying by average product prices (Bullard et al, 1978), which means that these values have been translated twice based on prices (the energy tariffs to translate the original IO data and now this), introducing more potential error. In general, studies employing this process have not been found to be comprehensive, and the selection of

which materials to further analyze is dependent on the intuition of the researcher (Lave et al, 1995).

IO-based hybrid analysis combines process-based and IO-based analyses in a different way in order to better address issues of downstream truncation that is experienced in process-based hybrid analysis. The direct inputs to a particular process are still determined using process data, and IO data is disaggregated to fill in any of the holes, upstream or downstream (Crawford and Treloar, 2003). Essentially, the materials that are accounted for in the process analysis are able to be subtracted from the IO data using an algorithm developed by Treloar (1997) to disaggregate the data, giving a more comprehensive picture and eliminate over- or under-counting any components.

Dixit et al followed up their 2010 article with further analysis of the need for standardization in embodied energy measurement (2012). Embodied energy databases suffer from problems of variation and incomparable data values. The International Standardization Organization (ISO) released an updated ISO 14040 and ISO 14044 to replace earlier standards in 2006. Despite the existence of these standards, there are still calls for development of separate standards for embodied energy analysis, as studies that explicitly follow the ISO standards still demonstrate considerable variation in their end results. This article reiterates the previously defined parameters that affect embodied energy results.

Additional areas of complication in analyses

Measurement difficulty also comes into play in terms of analyzing choices to reduce the lifetime energy consumption of a building. Most efforts to assess and reduce the energy consumption of buildings have looked at the operational phase, and both passive and active technologies have been suggested to curb operational energy use (Karimpour). Passive technologies include concepts such as building orientation, insulation, and day lighting. However, the thermal modeling of the efficacy of passive technologies is often wrong, and one study found the thermal resistance of insulated roofing systems to be half as effective as modeled (Belusko et al, 2011). This sort of error, in turn, requires additional materials, and therefore additional embodied energy, to correct after implementation. Inefficiencies in a particular building construction will

lead to increased operational energy for a given embodied energy. This means there is an increase in the proportion of embodied energy even when considering the actual operational energy used in a building.

2.2 Indian based studies

2.2.1 Indian building LCAs

The literature on buildings LCA in India is sparse but increasing. It shows a need for better, localized embodied energy data. A study on single, double, and 4-story residential buildings India looks at the energy burden associated with materials choices (Debnath et al, 1995). Because most of the literature up to the point of this paper came from industrialized nations with radically different climates (most notably, Sweden), the authors conclude that the statistics are expected to be drastically different in India, and that because most of the operational energy in the other buildings studied is from heat, that it is imperative to first consider the energy use for the production of materials and construction itself (i.e. the embodied energy).

The paper estimates the energy required for major building materials in India by evaluating the energy intensity of the industries involved in the production of the various materials, using an input/output-based analysis method. Then, using calculations provided by The Central Building Research Institute (CBRI) in India, the authors estimate the amounts of materials required for various floor plans and find that the energy content of the materials in construction in India is about 3-5 GJ/m^2, which is considerably less than the consumption of 8-10 GJ/m^2 in Japan. The authors attribute this difference to variations in production technologies and the greater use of human capital in India due to the use of traditional construction methods. The authors conclude that energy savings in buildings in India will therefore need to come from energy savings in the actual production of the materials in addition to decreases in day-to-day household activities.

A more recent study (Bansal et al, 2013) finds embodied energy in India on par with international studies, comprising 10-20% of the total life cycle energy. The data used for calculating the embodied energy comes from 2003, and the authors note that while it is preferable because it is India specific, it is incomplete: It lacks mining and transportation considerations, underscoring the need for updated embodied energy data in the Indian context.

2.2.2 Embodied energy of Indian building materials

Some headway has been made in the analysis and documentation of the embodied energy in the production building materials in India. The following sources provide insight into the most ubiquitous building materials, their production, and their environmental burdens.

A 2003 study looked at the embodied energy of both common and alternative building materials (Reddy et al). Reddy acknowledges the increasing demand for residential buildings in India, and asserts that minimizing the consumption of the conventional building materials will have a positive impact on the environment through considerable energy savings and decreased CO_2 emissions. He supports this claim through analysis of the embodied energy of building materials, which he characterizes as having three types: 1) energy in the production of building materials, 2) energy required for the transportation of the materials to the construction site, and 3) assembly of the component parts to form the building itself. Values are provided for the embodied energy of basic building materials (cement, lime, steel, etc.), as well as masonry materials (red bricks, stone blocks, cement stabilized earth blocks, etc.). Energy values for transportation are provided for individual materials, some based on volume and some based on mass. Finally, energy values are provided for mortars, which are typically mixtures of some of the basic building materials previously analyzed. The method for determining these values is not readily apparent, nor is the source of the data if these values come from other studies. The numbers are presented as deterministic figures. Reddy concludes that cement stabilized earth blocks—which he calls soil-cement blocks—consume 23.5% of the energy that red bricks consume. Additionally, because building materials may travel in excess of 100 km to urban centers in India, transportation could account for 5-10% of the embodied energy of red bricks, while the energy expended in the transportation of high-energy materials (steel and cement) is negligible compared to the energy required to manufacture them.

A report in the Institution of Engineers (India) Journal presents the embodied energy rates for a range of walling systems (Chani et al). The method for determining the embodied energy values for the component materials comes from a tabulation of data from Development Alternatives (DA), a nongovernmental organization focused on building “sustainable livelihoods” and the Building Materials and Technology Promotion Council (BMTPC). This data is from 1995. The

analysis concludes that red bricks are the worst choice in general regarding energy consumption. The authors also mention the depletion of top soil, as well as the damage of the ground due to the high temperature of the kilns, rendering land infertile long after the abandonment of a particular manufacturing site. They point to fly ash use in red bricks as a way to mitigate the top soil depletion concern, as well as an effective way to deal with a growing problem of fly ash disposal from thermal energy plants.

A Shakti Sustainable Energy Foundation and Climate Works Foundation supported study was published in 2012, providing a detailed assessment of the performance of the red brick industry in India (Maithel et al, 2012). The report is the first part of a two-part study that is meant to promote cleaner walling materials in India. The researchers monitored nine brick kilns over a four-month period (February to May) for energy performance, environmental performance, and economic performance. The parameters that were studied are clearly identified in the report. Seven of the brick kilns monitored were in India, while the remaining two—a tunnel kiln and a modified vertical shaft brick kiln (VSBK)—were in Vietnam, as neither of these kiln types were in operation in India. The researchers analyzed fuel usage to establish the specific energy consumption (SEC) for each of the kiln types (MJ/kg fired brick). Vertical shaft brick kilns (VSBKs) were shown to have the lowest energy consumption, followed by zig-zag kilns, fixed chimney bulls trench kilns, tunnel kilns, and finally, down draught kilns (DDK) which were shown to be four times less efficient than VSBKs. Particulate matter and gaseous emissions were also monitored, analyzed in a laboratory, and tabulated: CO_2 emissions had a hierarchy similar to that of SEC. Finally, financial analysis was based on the estimated capital costs for the kilns, the estimated production capacity of the kilns, and the typical payback period for each of the kilns.

The other component of this study was published in 2011 (Maithel et al, 2011), and focused on the environmental impact of assembled walls made from many different materials: red bricks, CSEBs, cement concrete blocks, autoclaved aerated concrete blocks, and a multiple fly ash varieties. The report looks at raw materials and resource consumption in the production of masonry materials, the energy consumed during production and transportation, air pollution from the production process, socio-economic indicators, such as the person-productivity hours for the manufacture of the components and the relative drudgery of the various labor processes, and the thermal conductivity of the materials as a proxy for estimating the operational energy required

for buildings built from them. Production processes for each material are described and the specifications for the size, weight, and composition of each unit is provided, as well as the number of units that are needed for a square meter of a wall assembly. The report first looks at these disaggregated indicators, and arrives at a number of conclusions: More use of waste materials decreases the overall resource consumption, as expected, and increased block size also decreases resource consumption. Red bricks have the highest embodied energy, and transportation is a significant factor in all walling assemblies. In general, fired materials have higher CO_2 emissions, but the variation in both the fired and unfired categories was found to be quite high. Considering a rattrap layout for red bricks significantly improved their environmental footprint overall. The report concludes by providing a number of policy recommendations for the promotion of cleaner walling materials, as well as the development of support networks for education of masons and builders.

2.3 Gap Analysis

As building LCAs become more commonplace, there is a need for reliable inventory data for the materials used in construction. In general, variation exists in the data that is found due to differences in components considered in individual studies. These differences may not be easy to ascertain since all of the components of a study are not readily annotated in individual studies. Therefore there is a need for a more systematic approach to the collection and analysis of this data, as championed by Dixit et al, with better standards involving the definition of system boundary and the choice of method of analysis.

Of course, particularly in India, but also worldwide, there is a general need for more data to be cataloged for materials used in building construction, as building LCAs will likely become more common in the years to come. Thus this data must be collected, ideally in systematic way that answers the issue described above. Indian-specific studies show increasing interest in the construction sector as a potential for energy and emissions reduction, but little work has been done to develop comprehensive embodied energy values to be used in LCA studies. In fact, much of the recent literature depends on deterministic values published in the mid 90's and the works of Maithel et al are the first to develop and report comprehensive, process-based analyses for the environmental impact of the production of building materials. While these studies

acknowledge differences in production methods and the impact of transportation on the environmental and economic impacts of the materials in question, they still provide deterministic values, taking into account limited differences in scenario. For example, they provide values for wall assemblies both with and without plaster, and they look at the effects of different kiln types and bond layouts for red bricks. However, the results are not readily tunable to different locations and production processes. Additionally, the analysis compares values across materials but does not dive into the individual factors that drive impacts for each material. Further analysis will be able to provide more comprehensive and more localized values based on the availability of local materials and the distance of travel, as well as a better understanding of the components of the processes to tweak in order to achieve more preferable environmental and economic impacts. Another area for future work will be continuation of the human labor studies in concert with increased interest in environmental impact, and Maithel et al have made a formidable start in covering this topic.

It is unlikely that the collection of this data will ever fully overcome the issues of variability that have been described. Development of methods that better utilize uncertain data is a way to address this issue from the other direction. Incorporation of uncertainty in LCAs is a recently-oft studied topic, particularly academically (Huijbregts, 1998 a and b; Lloyd and Ries, 2007). Further use of these methods in industry is one way to address this issue.

2.4 Research Question

The availability of comprehensive and locally relevant embodied energy data is crucial for credible LCA studies. It allows for confidence that analysis describes the situation at hand, and enables confidence in decision-making that might otherwise be plagued by nuances that could have adverse affects on the analytical outcome. This thesis looks at the production of red bricks and CSEBs to determine the factors that most drive the environmental and economic impact of each. The following research question is thus proposed: *Which are more environmentally and economically beneficial? Red bricks or CSEBs?* Specifically this thesis looks at:

- What aspects of the materials/production drive the impact of each and the comparison between them?

- How does the impact depend on which region of India we are considering, and how specific of a region must be considered?
- What is the impact of transportation on the overall environmental and economic burden?
- How does the use of alternative components or production practices impact the overall impact of a given material?

In light of the literature gap analysis, this thesis looks to compile data for the embodied energy of building materials in India, overcoming issues of applicability of the data. Furthermore, the chosen method of analysis incorporates variability in production method in order to address issues that arise with case study-based analyses. The analyses in this thesis are meant to be tunable for future research endeavors to allow for more specified studies. While the gap analysis highlights the need for additional study of the labor conditions as begun by Maithel et al, such analysis is beyond the scope of this thesis.

3 METHOD

3.1 Methodology

As described above, life cycle assessment is a tool to determine the environmental impact of a product over its lifetime. Carrying out a life cycle assessment requires inventory data for the components that comprise that product and the activities employed to realize those components. In the case of this thesis, a house is the product and the masonry units are the components that need to be inventoried. The goal is to evaluate the relative impact of two different masonry units: red bricks and CSEBs. To determine the preferential choice between red bricks and CSEBs in terms of environmental and economic performance, tunable, process-based models were developed to assess the production of both of these materials in either category, using information gathered about individual process steps. While the literature suggests the use of input/output data as a means of achieving more accurate, representative values, the disaggregated nature of the industries in question does not lend itself to this sort of analysis; the required economic I/O data, where it even exists, would not be representative of the existing players. Therefore, process-based models that allow for different production choices were the best route for this analysis.

The indicators calculated by the model were chosen based on their ability to communicate information of expressed interest to decision makers. Energy consumption in the production of these materials was considered despite its indirect relationship to environmental impact. In fact, embodied energy is an oft studied parameter, used as a proxy for environmental impact; it is also an easily communicated and understood parameter (Baumann and Tillman, 2004). Carbon dioxide emissions are another environmental indicator considered due to the international concern for a decrease in these emissions. Red bricks are fired in kilns producing visible smoke that has large quantities of carbon dioxide; CSEBs use cement, whose production creates CO2 from both the burning of fuel and the chemical reactions that take place during cement formation. Land-use was determined an important indicator to consider as growth will potentially lead to a depletion of arable land and natural resources; accounting for this could therefore serve as a useful tool before such dire consequences occur. Finally because adoption of new materials is likely to be purely market driven (once the efficacy of a material is demonstrated), cost analysis is necessary to ensure that new materials can be sold at a similar price to traditional materials while still turning a profit.

3.1.1 Functional Unit Definition

The first step in the analysis was to determine what exactly was going to be compared. In general, as already stated, the goal of this thesis is to compare red bricks to CSEBs. However, these materials are not exactly comparable in terms of technical performance. In fact, they are usually different sizes, with CSEBs being larger. Therefore, a red brick could not simply be compared to a CSEB because a different number of each would end up going into a wall of the same size. Thus, one square meter of walling was chosen as the functional unit to allow for comparison of results. Since the eventual application of the materials is walling, it makes sense to compare them in this context, and depending on the layout (or bond) of the bricks, the number of bricks and the amount of a mortar in one square meter will differ.

Maithel et al (2011) describe either the English bond or Rat-Trap bond as acceptable for the construction of load bearing walls of two stories with red bricks (230 mm x 115 mm x 75 mm) (Figure 3.1). That does not necessarily mean that this is how all dwellings are built, but it is what is considered structurally sound. Red bricks might also be laid out in a stretcher bond pattern (a

single course thick), which is considered safe for infill in a non-load bearing wall, but not for a load bearing wall. CSEBs (230 mm x 190 mm x 100 mm) on the other hand, because they are bigger, can be safely laid out in a stretcher-like formation, with the length of the brick (230 mm) constituting the thickness of the wall. However, just as it is possible to imagine red bricks being laid out in a way to minimize the number of bricks in a stretcher formation, it is possible that wide-spread use of CSEBs by self-builders could see the bricks laid out with the width of the brick (190 mm) as the width of the wall, regardless of the safety implications.

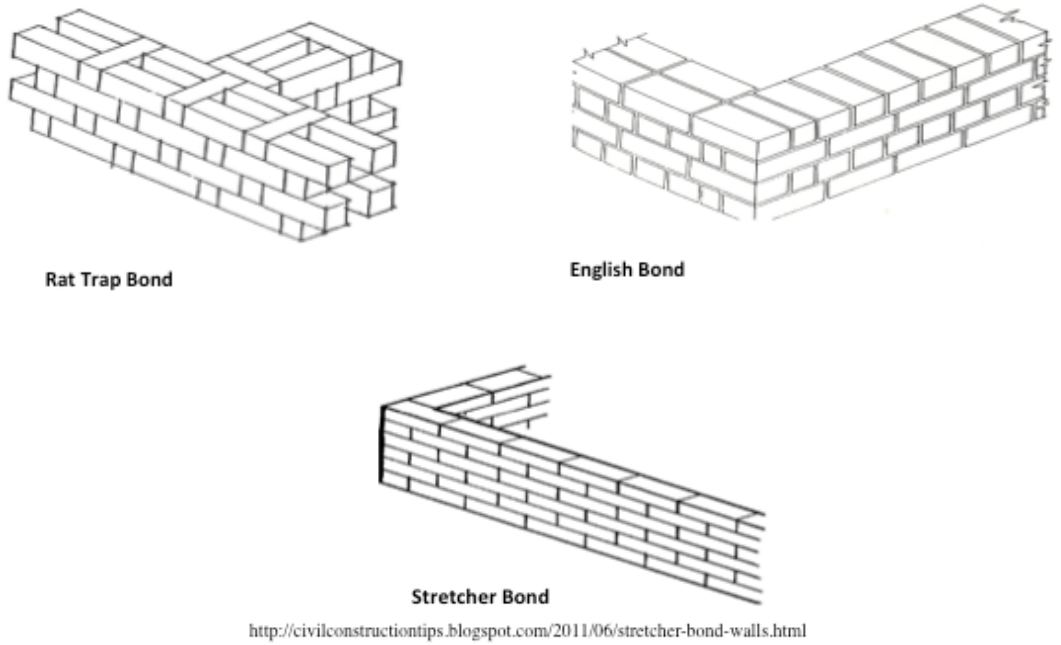


Figure 3.1 Walling assemblies

3.1.2 Data collection

Whenever possible, data sources were selected because of their relevance to the study in question—either because of geographic proximity or production process. The sources come from a variety of media, including academic literature, industry reports, and in person interviews during travel to various regions on India. Data was collected as both qualitative description of production processes as well as deterministic values of production amounts, consumption of raw materials, energy consumption, and carbon dioxide emissions when available. In some cases, regionally specific values were difficult to come by and data from ecoinvent (Swiss Center for

Life Cycle Inventories, 2012) were used in their place. Additionally, the software tool SimaPro (PRe Consultants, 2010) was utilized. This software takes the values in a given inventory and transforms them into their environmental impact.

3.2 Stakeholder analysis

In order to direct the subsequent analyses of this thesis, a stakeholder analysis was carried out. This analysis looked at the key players who have a stake in decisions regarding housing and the introduction of new construction materials into the market, and their relative power in the decision making process. This analysis is meant to further provide an understanding of the construction situation in India, as well as to target analyses toward answering questions of importance for those who will be instrumental in changing the landscape of how construction choices are made.

3.3 Red brick environmental and economic model

Following the stakeholder analysis, process-based models were developed for red brick and CSEB production to answer the relevant questions.

3.3.1 Production steps and system boundary

Understanding the process steps for brick production allows establishment of the system boundary. The six main stages of the brick making process accounted for in the study are:

1. Soil winning (extraction)
2. Soil-mix preparation
3. Molding
4. Drying
5. Firing
6. Transportation of the finished product

What follows is a brief description of the production of red bricks, regardless of kiln type used for firing.

Soil winning (excavation)

Soil winning is the process of soil mining, and thus marks the beginning of the brick making process. Typically, soil from agricultural fields is used for brick making, and the excavation process is performed manually. The depth of excavation is reported to be about 1 meter after the removal of the topsoil (Maithel, 2012).

Soil-mix preparation

During soil-mix preparation, water is added to the soil to achieve a moisture content of about 25-35% w/w. The soil and water are then mixed manually. It is during this stage that internal fuels, such as boiler ash can be added to the soil. While in traditional brick making, the soil and water is mixed by hand, literature on the use of internal fuels suggests that mechanized mixing is necessary for achieving the homogenous composition required when adding additional components to the mixture (Development Alternatives, 2012).

Molding

The clay mass is then molded into the shape of the brick through the manual, hand molding method. A small amount of sand (0.05% of the mass of the brick) is used to lubricate a wooden or metallic brick mold, and then the soil-mix is packed into the mold. The excess is then scraped off the top and the brick is removed from the mold (Maithel).

Drying

After molding the unfired green bricks are left in the open to dry, and they are eventually stacked until they are dried enough for firing. Their water content at the end of drying ranges from 3 – 15% w/w, and the speed of drying is highly dependent on the local weather conditions (Maithel).

Firing

The dried green bricks are then transported to the kiln for firing, where the temperature of the bricks is increased over a period of time, held at ~1000°C, and returned to ambient temperature.

The following are the general stages of the firing process (Brick Industry Association, 2006; Maithel):

1. Final drying (up to T=200°C), where residual moisture is evaporated from the green bricks, requiring energy input from the kiln.
2. Combustion of carbon materials inherent to the soil between 350°C and 700°C.
3. Decomposition of silicate-based minerals (found in clay), releasing chemically combined water (dehydration) (600°C).
4. Decomposition of calcium carbonate into calcium oxide and carbon dioxide. Calcium carbonate is a common impurity found in soil (600°C - 800°C).
5. Vitrification of the mineral components of the soil at their glass transition temperatures (which is below the melting point: 900°C - 1300°C).
6. Flashing or cooling is the final step in the firing process, and happens gradually.

Transportation of the finished product

After sufficient cooling, the red bricks are ready for transport to the construction site. Red bricks are reported to travel up to 400 km by truck to construction sites, and it is feasible as construction expands that this distance could grow even more.

3.3.2 Modeling the Manufacture of Red Bricks

A computational model was developed based on the steps outlined above. The model attempts to reflect the brick production process in detail. Based on the chosen layout pattern, the model calculates the number of bricks and the amount of mortar required to assemble one square foot of an assembled wall either with or without plaster.

Soil winning and soil-mix preparation

Because clay winning and soil-mix preparation are traditionally manual processes in India, they were not modeled as having environmental impact other than land-use due to soil extraction, which is captured by:

$$\boldsymbol{land_{use}} = \frac{\boldsymbol{volume_{soil}}}{\boldsymbol{depth_{extraction}}} \quad \textbf{(3.1)}$$

The land from which the soil is extracted is typically rented annually from local farmers and the quoted price for a bigha of land (1/50 of an acre) in Muzaffarnagar, Uttar Pradesh (shown in Figure 3.6) was used (22,500 Rs) to determine the raw material cost per brick of the soil. Maithel et al (2013) approximate that it takes 2-4 person hours to extract soil manually, so this value was used to calculate the wage paid to non-skilled workers per brick fired at a daily wage of 200 rupees.

However, as noted in the process description, when materials other than soil and water are part of the soil-mix preparation step, manual mixing is no longer sufficient for achieving a homogeneous mixture. Mixing can be achieved using a pug mixer or a tractor, and the rotation of both of these processes can be modeled using the same relationship to calculate the energy expended and the carbon dioxide emissions produced from burning diesel fuel (Zachau-Walker, 2013):

$$\boldsymbol{Energy_{mix}} = \frac{\boldsymbol{distance_{tractor}}}{\boldsymbol{volume_{soil}}} \boldsymbol{x} \frac{\boldsymbol{volume_{diesel}}}{\boldsymbol{distance_{tractor}}} \boldsymbol{x} \frac{\boldsymbol{Energy}}{\boldsymbol{volume_{diesel}}} \boldsymbol{x} \frac{\boldsymbol{volume_{soil}}}{\boldsymbol{functional\ unit}} \quad \textbf{(3.2)}$$

$$\boldsymbol{CO_{2mix}} = \frac{\boldsymbol{distance_{tractor}}}{\boldsymbol{volume_{soil}}} \boldsymbol{x} \frac{\boldsymbol{volume_{diesel}}}{\boldsymbol{distance_{tractor}}} \boldsymbol{x} \frac{\boldsymbol{mass_{CO_2}}}{\boldsymbol{volume_{diesel}}} \boldsymbol{x} \frac{\boldsymbol{volume_{soil}}}{\boldsymbol{functional\ unit}} \quad \textbf{(3.3)}$$

The calorific value of diesel fuel is used in **(2)** to find the energy required to mix the soil required for the functional unit, given the total distance the tractor travels. Similarly, the carbon dioxide emissions **(3)** are found using the emissions factor for burning diesel fuel. Either equation can be used to derive the amount of diesel fuel required to operate the tractor, which was used to calculate the fuel cost for motorized mixing during the soil-mix preparation step. This, along with the average cost of a tractor in India was included in cost calculations. The cost of water and the wages for drawing water, operating the tractor, and manual mixing were also included when calculating the costs incurred during soil-mix preparation.

Molding and drying

Molding is also a manual step, so there is no environmental impact in terms of additional energy expenditure or emissions. However, there is a cost associated with paying laborers, as well as the purchase of sand, which is required for lubricating the molds. Sand was assumed to travel a maximum of 50 km to the production site, and therefore environmental and economic costs are incurred due to this transportation. Environmental impact due to the extraction of sand came from the ecoinvent database, assuming industrialized excavation. Similarly, drying only incurs economic cost based on the labor required for the manual transport of the green bricks from the molding site to the firing site.

Firing

The environmental impact of firing the bricks is largely dependent on the efficiency of the kiln in which the bricks are fired, as well as the identity of the fuel source. For the purposes of this study, the fuel source was assumed to be coal, but empirical observation demonstrated that a wide variety of fuel sources are used for firing bricks and further investigation into the breakdown of different types of fuel sources (coal, wood, charcoal, agricultural waste products, industrial waste products, tires, etc) and their environmental impacts would prove crucial in providing a more representative picture of the actual impact of brick making as it is practiced today.

The specific energy consumption (SEC) of brick firing is the energy required for the firing of a kg of brick, and the values found by Maithel et al were used:

Kiln Technology	**Thermal SEC**	**Unit**
Down Draft Kiln	2.9	MJ / kg brick
Fixed Chimney Bulls Trench Kiln	1.22	MJ / kg brick
Tunnel Kiln	1.47	MJ / kg brick
Vertical Shaft Brick Kiln	0.95	MJ / kg brick
Zig-zag Kiln	1.12	MJ / kg brick

Table 3.1 SEC of different kiln technologies

Assuming coal as the fuel source allowed the use of an emissions factor for coal to derive the carbon dioxide emissions from the brick firing process due to the burning of coal. Additionally, some kiln types required electrical energy for the operation of conveyors and dryers, and the emissions factor of the Indian electric grid (0.82 kg CO_2 / kWh) was used to translate this energy consumption to carbon dioxide emissions (Krishnan et al, 2012).

Data about operational costs from interviews conducted in Muzzafarnagar were used to incorporate wages, and the capital cost of building a fixed chimney bulls trench kiln (FCBTK) was included.

As mentioned in the description of the mixing stage, additional materials can be added to the bricks as a substitute for clay. These materials can serve as filler materials, or as internal fuel. Boiler ash can be used as an internal fuel, combusting along with the fuel in the kiln to fire the brick "from the inside." Various sources suggest the use of internal fuel as a method to decrease the environmental impact of bricks through the reduction of fuel needed to operate the kilns, and also because they leave the finished fired brick less dense than traditional fired bricks, making them lighter and easier to maneuver (Maithel, 2011; Development Alternatives, 2012).

In decentralized industrial plants in India, where, as mentioned previously, there is a large variety of fuel mixes being used and the composition of these mixes is variable, the amount of unburned carbon is not only variable, but is also high due to the boilers not being optimized for the particular mixes in use. A study presented by Adhikari et al (2013) explored the use of charcoal as an internal fuel for red bricks made in a vertical shaft brick kiln (VSBK). The authors accounted for the amount of internal fuel in the bricks based on the SEC of the kiln and the calorific value of the charcoal, plotting the relationship between the amount of internal fuel used and the external energy required for firing the bricks:

$$\boldsymbol{SEC_{new} = -0.5277 * ash_{percent} + SEC_{baseline}} \quad \textbf{(3.4)}$$

The "new" SEC of the kiln can be found through this linear relationship of the percentage of the original SEC comprised by the internal fuel and the original SEC of the kiln. The percentage of the SEC comprised by the ash depends on the calorific value of the ash, and samples of boiler ash from a Bindlas Papers, a paper mill in Muzaffarnager, were analyzed and found to have a

calorific value of 4.8 MJ / kg. Adhikari noted that more research needs to be conducted to understand the relationship on the use of internal fuels and carbon dioxide emissions. Therefore, the red brick model currently accounts for the affect that internal fuel has on the energy consumption of the brick firing process and assumes that because carbon is still being combusted that the same conversion factors can be used to estimate carbon dioxide emitted to the atmosphere.

In terms of operationalization within the model, the input requested is the amount of boiler ash by weight. The model then calculates the amount of the SEC that is accounted for by the ash. Given the calorific value of the particular ash studied, 20% boiler ash by weight within a brick constitutes 98% of the SEC of a brick fired in a FCBTK, which means that higher percentages of boiler ash will lead to calculations of negative external energy requirements. For any given kiln type, a boiler ash composition by weight that exceeds the kiln's SEC is treated as filler material, and therefore has no further impact on the energy consumption of the kiln but still influences the overall raw material profile of the red bricks (and has an effect on the land-use component of the analysis).

Transportation of the finished product

Once the bricks have cooled in the kiln, they are ready for transport to their final destination and values for the environmental and economic cost of transportation were taken from interviews with brick makers in Muzaffarnagar and environmental analysts at Greentech Knowledge Solutions in New Delhi.

3.4 CSEB environmental and economic Model

3.4.1 Production steps

On a basic level, the production process for CSEBs follows the same steps as that for red bricks: soil excavation, soil-mix preparation, molding, and curing (instead of firing):

1. Soil excavation
2. Soil-mix preparation
3. Molding

4. Curing

There are a few differences between the two process expanded below.

Soil excavation

Soil excavation for CSEBs is more or less the same as red bricks soil winning, and is primarily a manual process.

Soil-mix preparation

After the soil is excavated, it needs to be sieved to remove any large pieces of gravel, and extra components might be added to achieve the appropriate composition (discussed later). Then the pre-determined amount of stabilizer is added to the soil and mixed until a homogenous composition is achieved. This is typically done manually, but the soil can be mixed in a concrete mixer, pug mill, or with a tractor, similarly to the mechanical ways that the soil-mix can be churned for red brick production. Once the soil mix is acceptable, water is added until the soil is sufficiently moist but not soaked.

Pressing

In this step the soil is loaded into a press and manually compacted (with the assistance of the press). Presses typically require 6-8 laborers to manage shoveling the soil, operating the press, and removing the finished blocks. Auroville Earth Institute has also developed a hydraulic press that requires the same number of people to operate but reduces the overall drudgery of the labor.

Curing

Once the blocks are removed from the press they are cured for about 28 days. CSEBs are modeled as being used locally because that is the market gap they are currently promoted as filling: They are materials that can be made at or near the construction site, cutting down on all of the issues that arise due to the transportation of bulky, heavy materials on a somewhat strained and inconsistent Indian road network. It is not infeasible to imagine that these materials, if produced on a large scale, could be shipped to their final destination, but the goal of those

currently promoting them is to provide jobs at a local level and to eliminate this need. Additionally, where CSEBs are currently in use, this is the practice, and the finished product does not travel more than 10 – 20 km (Maithel et al, 2012, AEI). Therefore, the model looks at the use of these materials locally, minimizing the need for shipping other than individual components that are required to achieve the ideal soil mix when necessary.

3.4.2 Considerations in Modeling the Manufacture of CSEBs

As with red bricks, a computational model was developed to calculate the environmental and economic impact of CSEB production, looking at the CSEB production process in detail. Then, given the bond layout, the model calculates the number of CSEBs and the amount of mortar required in one meter square of wall and determines the environmental and economic impact of the functional unit with or without plaster. Most of the process specifications come from the Auroville Earth Institute (AEI), and there are a couple of factors that affect the process.

Soil requirements

One way to characterize soil is by its composition of different size particles: gravel, sand, silt, and clay. Table 3.2 shows the size requirements for each soil component. The soil requirements of CSEBs are somewhat imprecise, but AEI provides ballpark percentage breakdowns for the particle size ratios that are needed (lime or cement), shown in Table 3.3.

Gravel	Sand	Silt	Clay
2 mm – 75 mm	0.05 mm – 2 mm	0.002 mm – 0.05 mm	< 0.002 mm

Table 3.2 Soil characterization by particle size

	Gravel	Sand	Silt	Clay
Lime	15%	30%	20%	35%
Cement	15%	50%	15%	20%

Table 3.3 Soil requirements for CSEBs

where gravel, sand, silt, and clay are different components of soil, categorized by particle size. The model requires input of a given soil breakdown and calculates the amount of additional

components that would need to be added to the soil in order to achieve the optimal mix. It is assumed that the maximum travel distance for these components would be 50 km. While lime can be used as a stabilizer for CSEBs, cement is more commonly available throughout India with standardized processing, and was therefore used as the stabilizer type in all analyses.

Press type

CSEBs are compacted in a large press that is either fully manual or assisted by a hydraulic mechanism. The different presses lead to different environmental and economic impacts for the entire system. First, hydraulic presses are made to require less effort to mold bricks, and allow for more bricks to be produced in a day. They also have a higher upfront cost. However, the hydraulic presses manufactured by AEI (Figure 3.2) are engineered to require the same amount of labor as manual presses, therefore not replacing part of the labor force with machines. Finally, hydraulic presses have higher compression than manual presses (average compression ratio of 1.9 vs. 1.7), increasing the amount of soil required to make a CSEB of the same dimensions.

Figure 3.2 Auram 3000 (manual) press from AEI; photo credit geocreate.eu

3.4.3 The process

Soil excavation and soil-mix preparation

Soil excavation for CSEBs is similar to that for red bricks, and is typically manual. It can, however, be mechanized, and it follows logically that if a particular producer has access to a tractor, he might use it for extraction. The model assumes that any additional soil components added to the soil-mix are extracted mechanically by tractor at an industrial scale. The environmental impact of using a tractor is described by equations **2** and **3**. Land-use is defined as the area of land used for the raw materials in the CSEBs (equation **1**), and is dependent on excavation depth. The cost of raw materials is embedded in the cost for land, and therefore considered independent of whether or not the soil components are excavated locally. It is the transportation cost that adds to the economic burden of needed additional soil components to be shipped in to the production site. The cost of land and the excavation depth was assumed to be the same as the costs in the case of red brick manufacturing. Labor requirements were calculated based on guidelines provided by AEI.

The environmental and economic burden of mixing is calculated in a similar way, and is dependent on whether mixing is manual or motorized with the use of a tractor. Upstream environmental impact of the components of the soil mix were considered, assuming industrial excavation of additional soil components that must be added to the mix. Values for the embodied energy and emissions due to the production of cement were also included.

Pressing and curing

As mentioned previously, the main variable in the pressing step is whether or not the press is hydraulic. The data for the cost and lifetime of the press and molds comes directly from AEI specifications. In either case, there is no additional energy (other than human energy) or emissions associated with the pressing step. Block removal, initial curing, and final curing do not have any environmental impact in terms of energy or emissions, and land-use in this study was limited to land consumed by raw materials excavation. The cost for these steps is limited to the amount of labor required to handle the CSEBs.

3.5 Soil type definition

For both red bricks and CSEBs, soil composition is the driving force behind whether or not brick manufacture is feasible with local materials. In general, soil is broken down into four

components that are defined based on particle size: gravel (20 – 2 mm), sand (2 – 0.06 mm), silt (0.06 – 0.002 mm), and clay (0.002 – 0 mm). Clay, in particular, is also defined by its mineral composition, and there are three main types of clays: kaolinite, smectite, and illite. The United Soil Classification System (USCS) lists three major soil classification groups: coarse-grained soils (gravels and sands), fine-grained soils (silts and clays), and highly organic soils. The Indian standard IS: 1498-1970, "Classification and Identification of Soils for General Engineering Purposes," only considers the first two groups, as organic soils are not suitable for engineering applications.

An oft-used means of assessing soil texture is the soil texture triangle, which is based on the clay, silt, and sand composition of the soil. A useful term to define when considering soil composition is loam, which is essentially a soil that is a mixture of the three components in no particular ratio. The soil texture triangle (Figure 3.3) shows different types of loam, characterized by their main component, for example clay loam or sandy clay loam.

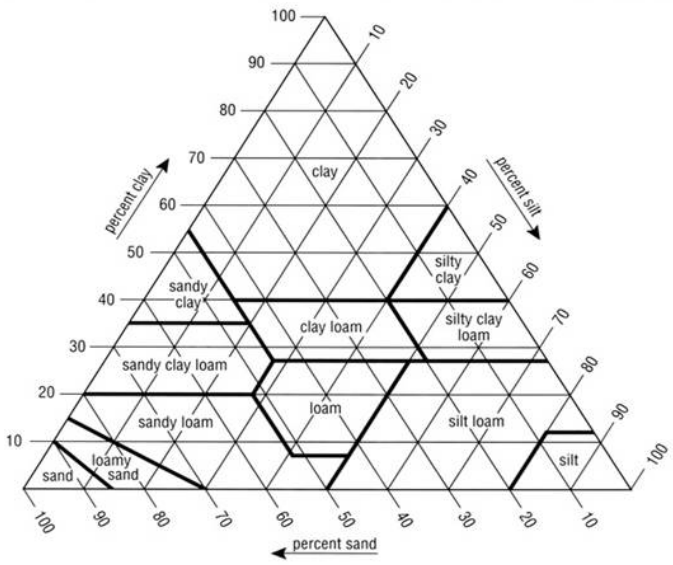


Figure 3.3 Soil texture triangle

While these soil classifications tell about the particle size composition of the soil, they do not tell about the mineral composition, which has a direct impact on the chemistry involved in the making of either type of brick. Therefore, further exploration about the efficacy of a particular soil-mix in the manufacture of red bricks and CSEBs is crucial before any production is attempted on a large-scale basis. In general, though, red bricks can be made with sandy clay

loam, loam, clay loam, and silty clay loam soils; and CSEBs work best with loam, sandy clay loam, clay loam, and sandy loam soils.

Soil mapping of India is based on the chemical composition and the nature of the soil's origins (and therefore does not directly indicate the particle-size composition of the soil in question). The dominant groups of Indian soils are as follows: red soils, lateritic soil, desert soil, alluvial soils, forest soils, and black soil. Qualitative descriptions of the soil types were used to determine relative ranges of clay and sand composition (with the remainder being silt) (Department of agriculture and cooperation (India), 2011):

Soil type	**Percent clay**	**Percent sand**
Red and yellow soils	25-40	20-45
Lateritic soil	35-50	15-35
Desert soil	0-30	60-100
Alluvial soils	5-35	35-80
Forest soils	5-28	30-52
Black soils	40-80	10-40

Table 3.4 Soil type – composition break down

The soil types corresponding with red brick production are red and yellow soils, alluvial soils, forest soils, and a small portion of lateritic and black soils (Mueller et al, 2008). The soil types corresponding with CSEB production are alluvial soils, desert soils, red and yellow soils, and forest soils (AEI). Because forest soils, though, comprise large amounts of organic matter, they really cannot be used for either type of production. Furthermore, excavation of forest soils would be significantly more complex than the aforementioned process, as removal of trees would need to precede any removal activities.

Comparison of a soil map of India (Figure 3.4) with a map showing the location of large-scale red brick production (Figure 3.5) corroborates these findings, as the majority of brick making endeavors are found in the alluvial soil regions to the North of the country (Development Alternatives, 2012).

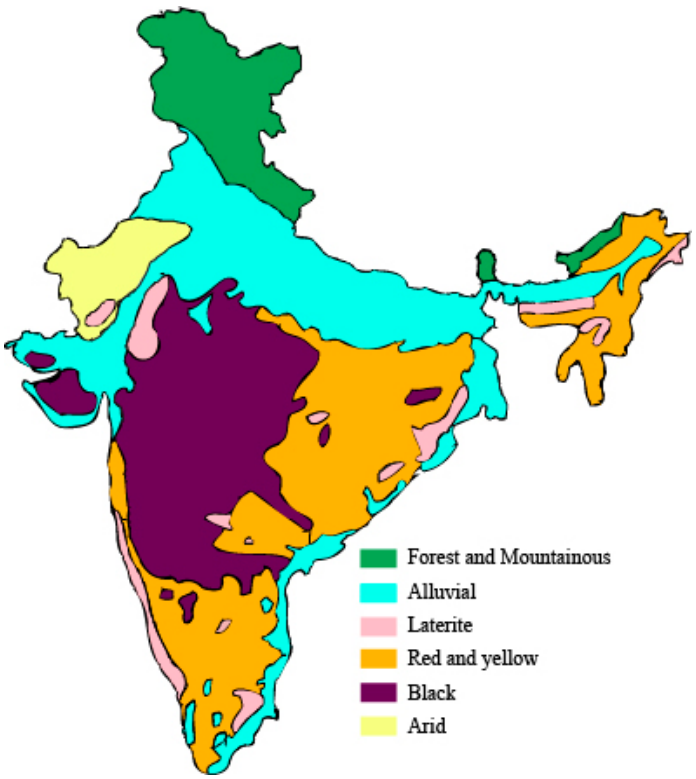


Figure 3.4 Soil map of the major soil types of India (adapted from data from the Ministry of Human Resource Development: Government of India)

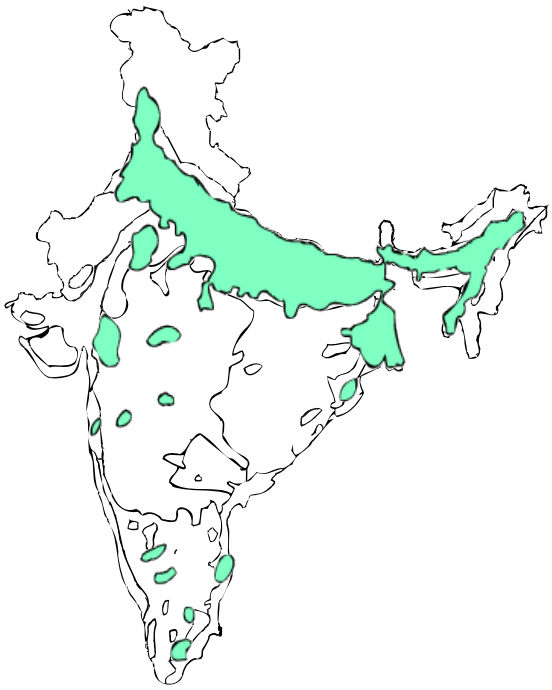


Figure 3.5 Map of India's brick making industry (adapted from Development Alternatives, 2012)

3.6 Experimental Design

Following the development of the computational models, a series of numerical experiments was carried out to progress toward answering the research questions posed at the outset of this thesis.

3.6.1 Sensitivity Analysis

Upon determination that both models were operational, the first analytical step taken was a sensitivity analysis of each by itself, manually looking at one variable at a time. The sensitivity analyses were meant to look at deviations in environmental and economic impact from a baseline value (determined based on status-quo practice) to understand which levers could drive the most dramatic change from basic values. These factors would then be used in subsequent experiments to observe their affects on various scenarios. In both red bricks and CSEB scenarios, it was assumed that materials for mortar and plaster (essentially cement and sand) traveled 40 kilometers.

In addition to the manual sensitivity analysis, Spearman's rank correlation coefficients were found for the variables mentioned above, using Oracle ® Crystal Ball to perform a Monte Carlo analysis for both models with 5,000 runs each. The same low and high values for each variable from the manual sensitivity analysis were used as parameters for the simulations. In addition to the four main indicators (embodied energy and carbon emissions, land-use, and cost per functional unit), the cost per individual masonry unit was explored. Although there is not much that can be done in terms of creating a structure with an individual brick, it is an important indicator in terms of economic viability of alternative materials, since purchasing decisions are typically made on a per-brick basis. In fact, particularly in rural parts of the country where access to savings instruments is extremely limited, investment in building materials provides an alternative way to secure funds. That is, individuals may regularly spend some of their earnings on individual bricks until they have enough to assemble a wall, or they might assemble it as the bricks accrue (Banerjee and Duflo, 2011). Therefore, while the cost of an assembled wall (or building) might be less for alternative materials like CSEBs, the unit cost can actually have an impact in purchasing decisions as long-term investments cannot often be made up front.

The Spearman correlation coefficient is the Pearson correlation coefficient between ranked variables. That is, the values of the variable in question (for instance, amount of sand found in the soil) are ordered, as are their corresponding outputs. In cases when there are multiple entries with the same value, the ranking is determined by the average of the positions they occupy, in ascending order. The equation for the Spearman correlation coefficient is:

$$\rho = \frac{\Sigma_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\Sigma_i (x_i - \bar{x})^2 \Sigma_i (y_i - \bar{y})^2}} \quad \textbf{(3.5)}$$

where x_i is the ranked variable, $\bar{x}$ is the value of the variable, y_i is the ranked output, and $\bar{y}$ is the value of the output. ρ is the Spearman coefficient. A perfect Spearman correlation is +1 or -1, with the sign of the coefficient indicating the nature of the relationship between the variable and the output (direct or inverse).

3.6.2 Red Brick baseline scenario

For red bricks, typical practice was determined through interviews with brick producers at Kisan Bricks in Muzaffarnagar, Uttar Pradesh, India. Traditional (manual) manufacturing processes were considered, and the raw material (soil) was assumed to be available locally. The dimensions of the bricks were 230 mm x 115 mm x 75 mm, and these dimensions appear to be ubiquitous throughout the literature and from inspection of bricks found throughout much of the Delhi and Muzaffarnagar regions. Additionally, because Muzaffarnagar is a brick producing area, it was assumed that the finished products were not shipped to their final destination. The kilns seen scattered throughout the landscape of Muzaffarnagar are FCBTKs and according to Maithel et al (2012), these kilns comprise about 70% of the kilns in operation throughout India and were therefore chosen as the baseline kiln type for the remainder of this study. It was assumed that the bricks did not travel significant distances by truck to their final destination and were instead used in town, and that they were laid out in an English bond formation for the ultimate wall assembly without the use of plaster.

3.6.3 CSEB baseline scenario

The CSEB business-as-usual scenario was developed following a training with AEI about production of earthen masonry. The dimensions taken for the CSEBs were described by Maithel et al (2011) as 230 mm x 190 mm x 100 mm. Although there is significantly less literature about these materials and even less current real-world production, the size of CSEBs is consistently reported as larger than that of red bricks. Because the walling layouts were suggested by Maithel et al, the dimensions the authors used for these bricks were also maintained. In this optimal situation, the local soil composition is perfectly suited to the manufacture of CSEBs and therefore no materials other than the stabilizer (and mortar for the assembled wall) would need to be shipped to the production site. Additionally, the excavation and mixing of the soil-mix was

assumed to be manual, and the press was also manual as this is the traditional way of making these materials. It was also assumed that the finished product did not require any transportation by truck, that the wall was laid out in the stretcher bond formation, and that the finished wall was not plastered.

3.7 Geographic Scenarios

Because most of the empirical information for this study (particularly about red bricks) comes from Muzaffarnagar and a main focus of the research is to understand the viability of CSEBs as an alternative to red bricks, Muzaffarnagar was chosen as the region to perform a case study-type analysis. The soil type in Muzaffarnagar is predominantly alluvial, and the composition of the soil was determined based on the soil map analysis as described above, using the minimum, median, and maximum percentages of sand in the soil as three different potential values for the local soil mix. Any components that would need to be added to the soil were assumed to travel no more than 50 kilometers, as this is reported as the maximum value sand typically travels to a construction site (Maithel). In addition to Muzaffarnagar, Hyderabad, Andhra Pradesh, and Nagpur, Maharashtra were explored because of their different geographic locations (shown in Figure 3.6), proximity to industrial red brick making, and different predominant soil composition.

Monte Carlo simulations were performed using Oracle ® Crystal Ball as they were to provide values for the calculation of the Spearman coefficients. The parameters for the simulations were the same as those used for the manual sensitivity analysis, giving equal probabilities to the low, medium, and high values in each case (or low and high when there were only two). The trial values from these simulations were used to determine the range of possible values for each of the indicators in question. From here, and using the knowledge about the main drivers for each indicator, different scenarios were explored.

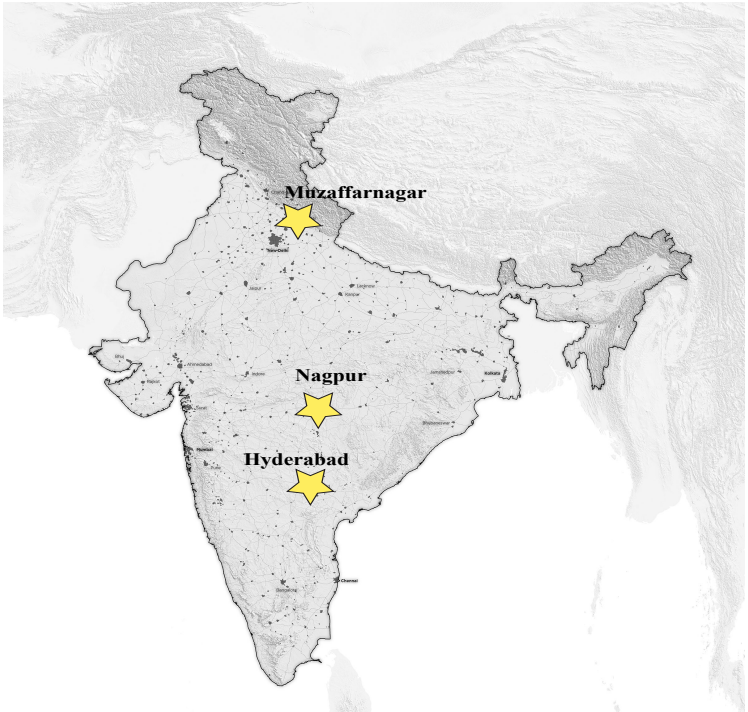


Figure 3.6 Map showing the location of Muzaffarnagar, Hyderabad, and Nagpur (Natural Earth, 2014)

4 STAKEHOLDER ANALYSIS

While analysis of the environmental impact and cost tradeoffs for different materials is crucial for understanding both the potentials and bounds of resource management and environmental conservation, understanding the collective action problem in addressing these concerns is also important. A collective action problem is one in which the solution will benefit a large group, bu also requires significant coordination—something like the "drop in the bucket" saying (Olson, 1971). If every person put a drop in a bucket, it would eventually fill up, but seeing the contribution of one individual is difficult, leading many to forego participation. Such is the case with the issues of environmentalism and climate change: It is easy to write-off an individual's actions as being such a small part of the whole that they are negligible. Therefore, the target audience is only a subset of the stakeholders: those who have an interest (conscious or otherwise) in the eventual effect that the analysis and the ability to coordinate in order to affect change. This analysis will inform decisions about the target audience for this and further exploration of the cost and environmental tradeoffs in building materials choices.

The interested parties can broadly be broken into four categories: the government/government officials, non-government organizations (NGOs), industry, and consumers. It is useful to address each group in turn to gain a better understanding of the stakeholders' potential interest in this work, the importance to decisions made by the stakeholder, and the influence the stakeholder has on the overall system.

4.1 NGOs

Nongovernment organizations (NGOs) operate in a variety of spaces that affect housing construction. There are those focused on affordable housing and community development, those concerned environmental conservation, and those that provide financing (or coordinate it) for projects in the form of microloans. While these are three separate categories, NGOs in these spaces can work together or a single NGO can function in multiple capacities, as is the case with Development Alternatives in Delhi whose mission is to promote sustainable livelihoods through sustainable building techniques and employment development. Micro home solutions is another NGO working in this space that works to coordinate financing options for affordable housing projects while also promoting safe building techniques. An NGO's specific function in this space informs its interest in materials selection metrics, and it is valuable to look through each lens in turn.

Strict interest in affordable housing leads to a need for understanding the costs of materials. As environmental concerns increase and resources are depleted, price volatility is a real concern. Honing in on the main drivers of cost for materials will allow project managers to make better decisions throughout the lifetime of a given project. Materials that can be used effectively and efficiently are ideal, and these organizations will likely have an interest in the overall cost of a project.

It is important, however, to acknowledge building habits in India. While there are many projects that involve building houses and giving or selling them to low-income families, there are also projects that capitalize on the Indian tendency to self-build (micro home solutions, 2011), and NGOs operate to facilitate conversations between future homeowners and hired masons and permitting authorities. These, along with NGOs that facilitate access to financing are interested

in the "affordability" of the construction process. That is, regardless of the final cost of the house, a house is still built brick-by-brick (or masonry unit-by-masonry unit), and there is a need to determine how much is reasonable for an individual to pay at one time. Thus, it is important for decision makers to understand costs at different scales of a building project in order to better determine what customers are able to afford when developing financing schemes.

NGOs that have an interest in environmental impact in addition to providing low cost housing options are also concerned with the effects of resource consumption and materials production that have yet to be robustly researched. While there is a general trend of acknowledging the environmental (and cost) impact of transportation of raw materials and finished products, it is not always true that "local" means less overall environmental impact (DeWeerdt, 2009). Given the soil variation throughout India and the overall climatic diversity, environmentalists need a way to localize analysis of environmental impact beyond the case study examples that currently exist, since they may not be locally applicable.

NGOs play the important role of making many decisions on the ground. Though they are not particularly organized (across organization lines), they are currently found throughout India, working on numerous housing initiatives. Thus they have the power to influence the system on a localized level through purchasing decisions and development of cooperatives. NGOs have much lower potential to revolutionize the entire system, however, as they are particularly disaggregated and don't wield considerable power on the political stage. Given the difficulty with enforcement (as opposed to regulation), NGOs could very well be the most important stakeholders, as bottom-up approaches are likely the best option for revolutionizing housing since government schemes have not been very successful.

4.2 Government

The Indian government has demonstrated an interest in developing affordable housing options for the vast number of low-income families throughout the country through various initiatives (The World Bank, 2013). These large-scale projects require an eye for urban design, which has materials' requirements that consider aesthetics and cultural norms (in addition to structural

needs). While there might be a true interest in using the most cost effective and/or environmentally friendly building materials, historical norms

A major concern for the Indian government is electricity usage. Of further concern is the environmental impact of production processes. Rapidly developing nations, such as India and China, will continue to feel pressure from the West to decrease greenhouse gas (GHG) emissions. Consideration for decreasing GHG emissions can, in turn, lead to consideration of preferred fuel sources and pollution control technologies.

All of these factors can play into decisions made by the government, and it is important that these factors are backed up by sound analyses, as common, simplified assumptions about environmental impact are not universally true.

Government has the power to issue regulations, and ultimately enforce them. Distinguishing between regulations and enforcement is particularly complicated given the disaggregated and informal nature of much of the building materials sector. Government officials, therefore, also have an interest in cost analyses that can pinpoint opportunities for further innovation or process optimization that will allow for better environmental performance at lower costs. Given the development of these processes, the government will have less to do by way of enforcement, as industry behaviors are driven by the bottom line. Conversely, given strong enforcement (and less corruption), the government would have a large influence on building materials choices.

State governments also have an interest in promoting local industry, and any analysis of costs and/or environmental impact can be used to justify policies that will benefit local producers and potentially increase their market share. Of course, there is the concern that analytical results that can be locally tailored can be tweaked to argue in any direction, and it is very possible that a government official's interest in promoting local industry is not merely altruistic (or only for the good of constituents). He may very well have a stake in local industry.

In theory, government has a large opportunity to affect change in this space (and others). However, given India's issues with enforcement (and corruption) (Duflo et al, 2013), government is not the ideal target audience of this type of analysis or analytical tool—at least not on its own. Implementation of results taken from this research in concert with efforts targeted at

addressing corruption and enforcement concerns could be of value, and in that way the government and/or government officials could be targets. This would involve interfacing either with NGOs or researchers implementing such programs, though, and therefore the government as a single entity remains a distant stakeholder.

4.3 Industry

There are multiple industrial players that would be affected by the results of this analysis and changes in consumer habits regarding building materials choices. This group includes raw materials miners, transporters, brick manufacturers, brick kiln owners, cement manufacturers, and many others. Each group has its own, potentially distinct, stake that can be analyzed, but there are a few broad strokes that are common to various groupings.

Labor

Laborers of course have an interest in any changes in industry, particularly those regarding production choices and techniques. This is of particular concern when thinking about alternative choices to affect environmental impact. Manual processes will typically have lower environmental impacts, but require more manpower. Interestingly, though it is often assumed that labor is cheap and plentiful in India, there is a manual labor shortage. In fact, one survey claims that the labor shortage will rise by 65% in the next 10 years due to movements of the labor force out of traditional sectors and into the service industry (The Indian Express, 2013). Additionally, the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) is often cited by industrialists as influencing this labor shortage because of decreased migrations and demands for higher wages (The Economic Times, 2013). This act provides some financial security for individuals residing in rural areas, providing at least 100 days of guaranteed labor for each household where adult members volunteer to perform unskilled work (Ministry of Rural Development, 2005).

Regardless of the cause of the labor shortage, the fact that it exists will encourage movement to more automated practices in various industries. This could be problematic if further labor reforms encourage moves back to industries that no longer have jobs for would-be employees. Furthermore, if some production lines become automated and are able to capitalize on economies

of scale, lines that are not automated may be forced to update, further affecting those who still seek out labor in brick production, for example. Needless to say, there are numerous ways that the landscape of employment in materials production could be affected for workers if changes in materials choices become pervasive. If the knowledge of the extent of environmental degradation due to mining of raw materials leads to further regulation of the mining industry (or movement away from raw materials use) laborers in this industry will need to find other work. Regardless of the effects of this analysis, though, remains the fact that there are overarching social policy factors that will undoubtedly affect this sector.

Despite the large stake that laborers appear to have in any outcome resulting from the analysis of this research, they have relatively little bargaining power to affect change in the system. This is a further reason why NGOs that have interests in livelihoods and the well-being of laborers are an important stakeholder to target because they will be best suited to speak on behalf of these laborers.

Production line owners

Any production line owner (taken to be those who run operations in mining, masonry unit production, cement production, and so on) will of course be affected by any changes in habits or policy that move consumption toward or away from their products. Particularly interested parties could play a role in the development of more economic or environmentally efficient techniques or materials that take advantage of the infrastructure in which they have already invested. Additionally, understanding the systems nature of materials production and consumption could lead to economically beneficial choices as manufacturers are able to identify cost-saving potentials. Since these producers are market driven, any insight into future policy or demand trends can help them adapt to future changes and become competitively positioned. While probably not the direct target audience of this type of analysis, these stakeholders are crucial for determining alternative possibilities for production that take advantage of existing infrastructure and supply chain networks. Future systems analysis taking into account the results of this analysis and the existing networks used by these producers can allow for further cost and resource savings in this space, and potentially others. Some production line owners are a part of a particularly disaggregated system (brick kiln owners, for instance) and have little effect on the

whole system through individual decisions. Others, like cement producers, have large market shares and therefore can more easily affect the system through individual changes. This is one reason why changes and upgrades in the cement industry have been fairly ubiquitous in India, and Indian cement production is state-of-the-art in environmental controls (Twigg and Trudeau, 2012). The more aggregated industries have more power to influence the system than others. Given this fact, they will have more power to champion alternatives that are proposed and developed as a result of the analysis (or not), and could be an interesting group to target, depending on the outcome of the analysis.

4.4 Consumers

Consumers, as the ultimate residents of houses, are stakeholders in the decision making process as so much housing in India is self-built (up to 60% in major cities and more in smaller towns, according to micro home solutions), giving these consumers pretty direct impact in the materials decisions. That said, low-income consumers likely have little influence in formal decisions that are made regarding housing (such as the development of sites-and-services projects and the allocation of plots, or the building of high-rise low-cost apartments). They have considerably more influence in the informal sector of incremental additions to housing they either purchase or are given by the government. Of course, they are also driven by costs as well as access to (or lack thereof) financial instruments (like savings accounts). Another important note, as reiterated by numerous in-person interviews, is that people are generally reluctant to change, particularly in terms of how and with what they build their houses. That is, there are a lot of ideas about red bricks, such as the redder the brick, the better, that are more in the psyche of the public than established engineering facts. There is a bit of a stigma against any sort of new materials, which means that their efficacy as well as their cost effectiveness must be adequately demonstrated before the masses will be interested in change. Members of the Central Building Research Institute (CBRI) in Roorkee stressed the importance of pilot projects that heavily engage the community as a key way to introduce new materials into the self-building tool kit.

In terms of exerting influence on the entire system, consumers face a collective action problem in the sense that they are rarely organized beyond small communities. Additionally, they have so

many concerns that as long as they have satisfied their basic shelter needs, it is unlikely that they will look to organize in order to revolutionize the housing system.

Higher income consumers are beginning to show interest in environmental building options, as demonstrated by billboard advertisements throughout the Delhi area for "green communities." These communities are built by developers, and these developers can better assess the "greenness" of them through the analysis of the embodied environmental impact of the building materials that they use. It is worth pointing out that low-income aspirations are often influenced by higher-income realities. Therefore, while it might seem sensible to push alternative options for the masses requiring low-cost housing, there is the potential to influence low-income self-builders by furthering the use of environmentally preferable materials in higher income housing.

Homeowners are the epitome of a disaggregated stakeholder in this context, and therefore wield little power as individuals to affect change in this space. Still, their desires and concerns must be kept in mind when developing parameters for any analysis regarding house construction and building materials choices.

Developers and Architects

As mentioned above, most of the housing stock is self-built through the hiring of contractors and masons (or truly by laying the brick by hand). But in higher income sectors there are Western-style developments and the use of architects for planning and designing construction. These players are therefore part of the materials decisions for a project, and are driven both by costs and consumer demands. They also have the ability to influence consumers if working on individual projects. Therefore, certain architects and developers who work in concert with environmental NGOs (or who have general concerns or interests in the environment) would be valuable targets for the results of this analysis.

4.5 Summary

This cursory analysis of stakeholders in building materials choice shows that there is a wide variety of interest in the space. As might often be the case, those with the biggest interest in changes to the status quo have little power to affect this change. Because of the disaggregated

nature of much of the industry and the difficulty that the government currently has with enforcement and corruption, it seems that NGOs are the most promising target audience of this analysis.

As described, NGOs can have a variety of targets, and it is precisely this variety that makes them so desirable. Of course, the interest of this analysis is first and foremost environmental impact, but the goal is also to enable better materials choices for low-cost housing, and therefore to provide better shelter opportunities for the scores of people currently living in inadequate conditions. Therefore, the cost tradeoffs of different materials and production choices are of crucial concern. New materials must be cost competitive in this market, which has little room to opt for pricier, but more environmental choices. Furthermore, NGOs that focus on financing options for the poor will be able to use the results of this analysis to better negotiate terms of financing as they struggle to work within the bureaucratic schemes required when implementing housing projects. Finally, there must be a focus on the welfare of the labor force and NGOs that advocate for low-skilled and unskilled laborers will be interested in any analysis that can affect typical production techniques and the employment market.

5 RESULTS

As outlined in the description of the methods used for analysis, a series of steps was carried out to understand the drivers of environmental and economic impact of CSEBs. The results of these analyses are discussed below.

5.1 Sensitivity analyses

Starting with base scenarios for red bricks and CSEBs, sensitivity analyses were performed to look at the effect of changing one variable at a time based on the variables described below. From the sensitivity analyses, it is possible to draw conclusions about the variables that must be considered when comparing the two materials.

For red bricks, the variables that need to be explored are:

- Bond type of the walling assembly (Stretcher, Rat trap, or English bond)

- Kiln type (Tunnel, FCBTK, or VSBK)
- Internal fuel use (20% or 0%)
- Transportation of the finished product (0 km, 250 km, or 500 km)
- Whether the finished wall is plastered (yes or no)
- Excavation depth (0.75 m, 1.5 m, or 3 m)

The variables that require further scrutiny for CSEBs are:

- Amount of stabilizer (4%, 7%, 10%)
- Bond type of the walling assembly (width-wise stretcher or length-wise stretcher bond)
- Stabilizer identity (Ordinary Portland Cement (OPC) or Portland Pozzalana Cement (PPC))
- Method of extraction and mixing (with or without tractor)
- Whether the finished wall is plastered (yes or no)
- Local soil composition: amount of sand in the soil(low, mid point, high based on soil type)
- Press type (manual or hydraulic)
- Extraction depth (0.75 m, 1.5 m, 3 m)

In total there are 14 different parameters that appear important for the various indicators. Two of them are determined by the location of assembly of the functional unit: transportation distance of finished red bricks and the local soil composition (as it impacts CSEB production, assuming that CSEBs are produced at a construction site or nearby enough that the effect of transportation of the finished product is negligible). However, the soil type indicates a range of soil compositions and therefore still needs to be considered in further sensitivity analyses. Below, the levers driving the impacts for each product are discussed as results of the sensitivity analysis, along with their Spearman coefficients from the dynamic simulations.

5.1.1 Baseline values for red bricks and CSEBs

As mentioned in the chapter on methods, the base case for red bricks considers an English bond layout, which corresponds to 98 bricks per square meter of wall. For red bricks in Muzaffarnagar

(using a FCBTK and requiring no transportation to the final construction site), the model calculates an average energy consumption of 430 MJ per square meter of wall and carbon dioxide emissions of 44 kg per square meter of wall. The base case land-use is 0.22 m^2 per square meter of wall, due to extracted soil. The production cost for one square meter of wall is 396 rupees.

Embodied energy	430 MJ
Embodied carbon dioxide	44 kg
Land-use	0.22 m^2
Production cost for one square meter	396 Rs

Table 5.1 Red brick base case values

In addition to the sensitivity analysis of the cost of the functional unit, the cost breakdown for an individual brick is shown in Figure 5.1:

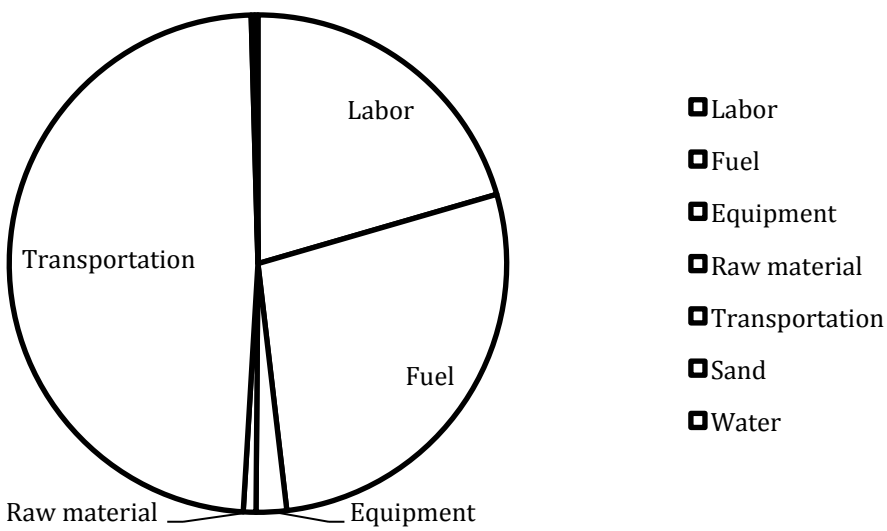


Figure 5.1 Cost breakdown of red brick production (categories listed clockwise from labor)

As seen in the cost breakdown, fuel accounts for more than half of the cost of red brick production, with labor as the other major factor in the cost. The distance that the bricks travel has a Spearman ρ coefficient of 0.94, showing that cost is heavily impacted by the transportation of the bricks. This is not seen in the above cost breakdown because it is the breakdown of the base

case scenario for which there is no transportation. The effect of transportation on cost will be further explored in later analyses.

The base case for CSEBs requires 46.2 bricks for a square meter of walling. For CSEBs that do not require materials (other than cement) to be transported to the manufacturing site (in other words, CSEBs that can be produced using all local materials), and use only manual labor and a manual press, the model calculates an embodied energy value of 175 MJ per square meter of wall and carbon dioxide emissions of 37 kg per square meter of wall. Base case land-use is 0.16 m^2 per square meter of wall, and base case cost is 359 rupees per square meter of wall.

Embodied Energy	175 MJ
Embodied Carbon Dioxide	37 kg
Land-use	0.16 m^2
Production cost for one square meter	359 Rs

Table 5.1 CSEB base case values

Breaking down the cost of CSEB production into its components shows that the cost of the stabilizer is the largest contributor to the cost of a CSEB that is otherwise made with all local materials (**Error! Reference source not found.**). The spearman ρ coefficients, shown in Table 5.2, show that stabilizer does, indeed, drive the cost of the production of individual CSEBs the most, followed by the press type, the amount of materials that need to be added to the local soil, and the method of mixing and extraction.

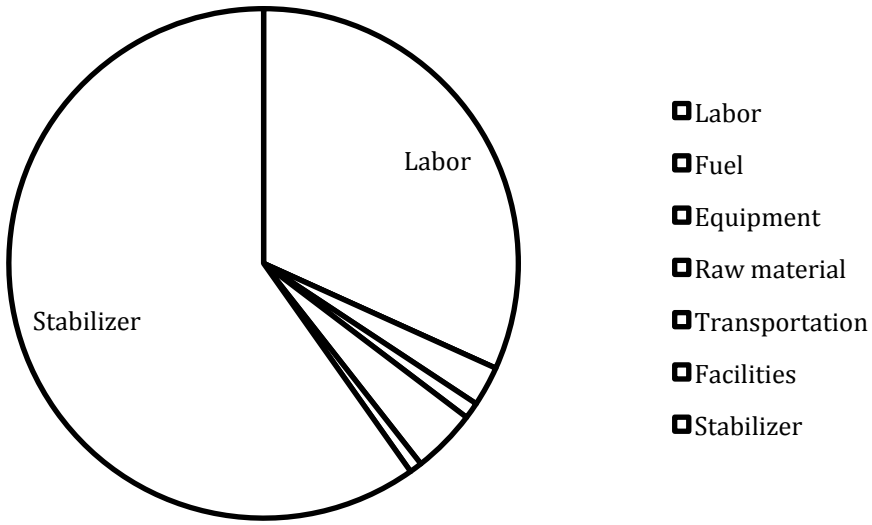


Figure 5.2 Cost breakdown of CSEB production (categories listed clockwise from labor)

Variable	Spearman ρ	Prob>| ρ |
Amount of stabilizer	0.8127	<.0001
Press type	-0.347	<.0001
Amount of sand in local soil	-0.1881	<.0001
Mixing and extraction	0.1774	<.0001

Table 5.2 Spearman ρ values and p-values for variables affecting CSEBs' cost per brick

5.1.2 Sensitivity analysis: red bricks

Energy sensitivity

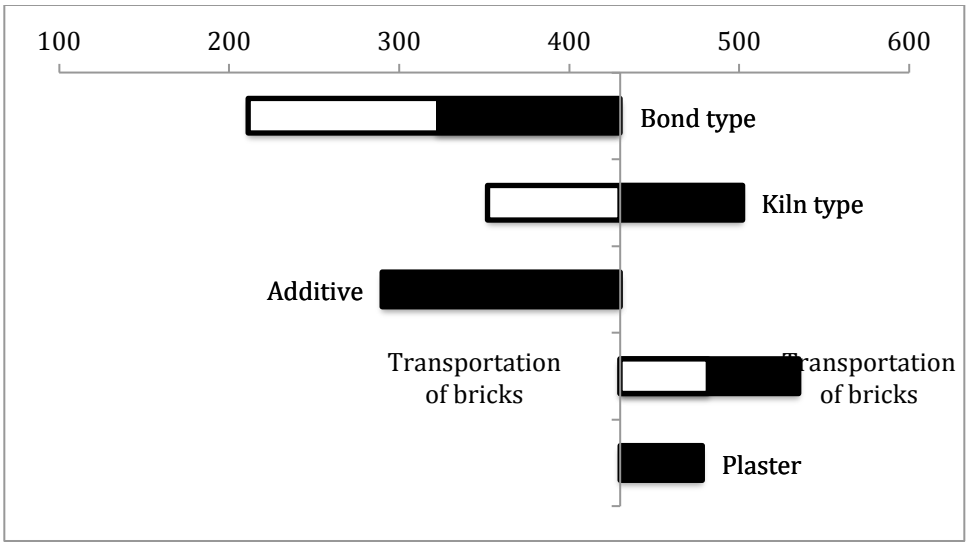


Figure 5.3 Embodied energy (MJ) sensitivity of red bricks

Figure 5.3 shows the relative effects of the different variables affecting the sensitivity of embodied energy for red bricks. The biggest driver of deviation from the base case energy consumption is the bond type chosen for the wall assembly, which simply determines the number of bricks to be used in the wall. The lowest energy consumption is caused by a stretcher bond, which calls for half the number of bricks as the English Bond, and the rat trap bond, which calls for about ¾ the number of bricks as the English Bond, is the midpoint on the tornado plot for bond type. The kiln type, which serves as a proxy for firing efficiency, had the next largest impact on the energy consumption, with vertical shaft brick kilns (VSBK) having lower energy consumption and tunnel kilns having higher consumption than FCBTKs. The inclusion of the additive lowered the energy consumption of the bricks because of its effect as an internal fuel. The transportation of the final product (either 250 or 500 kilometers) has the next substantial effect on energy consumption, and the addition of plaster to the wall has final effect on energy consumption shown in the tornado plot.

The dynamic simulation yielded Spearman ρ values that, for the most part, corroborated the general trend of the sensitivity analysis (Table 5.3). However, variations are seen that are due to the fact that variables are changing in concert with each run of the simulation, which can either amplify or dwarf the effects due to changing them one at a time.

Variable	Spearman ρ	Prob>| ρ |
Bond type	-0.7185	<.0001
Additive	-0.4058	<.0001
Transportation of bricks	0.2603	<.0001
Kiln type	-0.2204	<.0001
Plaster	0.1899	<.0001

Table 5.3 Spearman ρ values and p-values for variables affecting red bricks' energy consumption

The bond type, by far, has the largest impact on the embodied energy, and the use of an internal fuel can have the next biggest impact. Transportation of the finished product, kiln type (or kiln efficiency), and whether the wall is plastered round out the top five drivers of embodied energy.

Emissions sensitivity

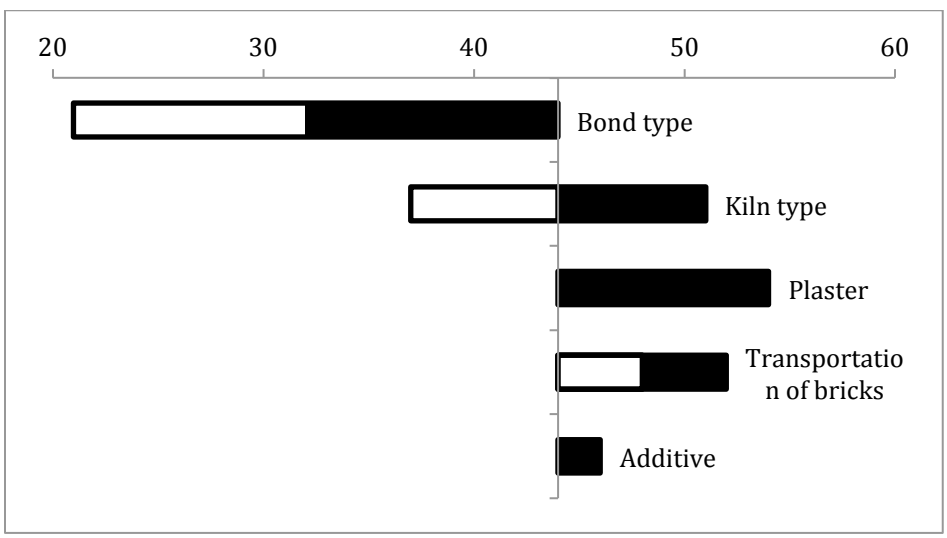


Figure 5.4 Carbon dioxide emissions sensitivity of red bricks

Figure 5.4 shows a similar pattern in the carbon dioxide emissions' sensitivity to the energy sensitivity. Change in the bond type leads to the greatest deviation from the base case, followed by kiln type, plaster, transportation, and additive. Inclusion of an additive in the bricks leads to lower sensitivity in the case of emissions than it does for energy because of the limited data available for determining general trends for the effect of using an additive on carbon dioxide emissions. In fact, the addition of internal fuel to the red bricks actually is shown to increase the emissions profile for the red bricks from the base case because of the emissions due to the

processing of the ash before it is incorporated into the bricks. This is not seen in the energy profile of the red bricks because the energy reduction from the use of an internal fuel outweighs the energy requirements for the grinding of the boiler ash before it is incorporated into the bricks.

Variable	**Spearman ρ**	**Prob>| ρ |**
Bond type	-0.8404	<.0001
Plaster	0.3786	<.0001
Kiln type	-0.1813	<.0001
Transportation of bricks	0.1684	<.0001
Additive	0.0709	<.0001

Table 5.4 Spearman ρ values and p-values for variables affecting red bricks' embodied carbon dioxide

Again, the Spearman ρ (Table 5.4) for each variable shows a similar trend as the sensitivity analysis, with the bond type having the greatest affect on the embodied carbon dioxide emissions of the walling assembly. The plaster and kiln type are switched relative to their place on the tornado plot. And the transportation of bricks and the use of internal fuel round off the final entries. It is important to note the correlation between the use of an additive and the embodied carbon dioxide emissions: It is a positive value, as discussed above.

Land-use Sensitivity

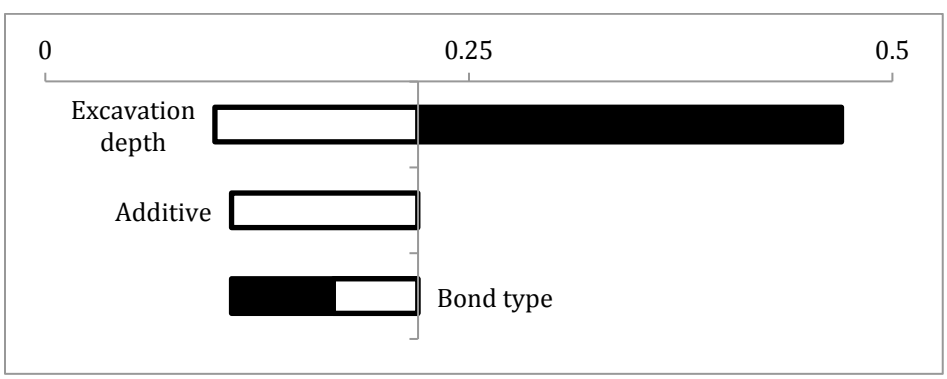


Figure 5.5 Land-use (m^2) sensitivity of red bricks

Figure 5.5 shows that deviations from the base case for land-use are mostly driven by the excavation depth, which ultimately affects how much of a space is occupied for extraction, and

the use of an additive, which affects how much soil is needed per brick. Finally, of course, bond type affects the amount of land-used for the functional unit because of the change in the number of bricks.

Variable	**Spearman ρ**	**Prob>| ρ |**
Excavation depth	-0.917	<.0001
Bond type	-0.3445	<.0001
Additive	-0.1086	<.0001

Table 5.5 Spearman ρ values and p-values for variables affecting red bricks' land-use

The Spearman ρ values seen in Table 5.5 show that excavation depth does have the greatest impact on land-use, by far, and that the bond type actually correlates to the land-use three-times more than the use of the additive.

Cost Sensitivity

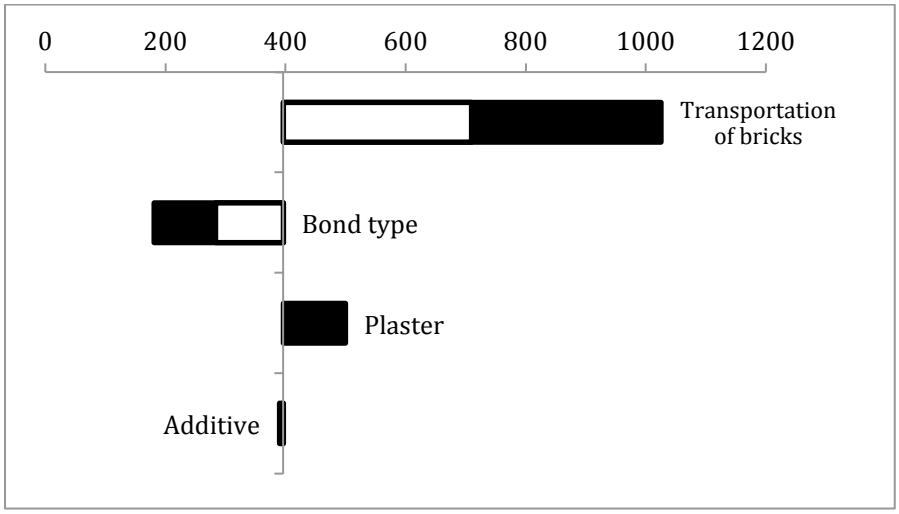


Figure 5.6 Cost sensitivity (Rs) of red bricks

Transportation is shown to drive the largest deviation from the base value of economic cost for the functional unit in Figure 5.6, followed by the bond type of the wall itself. Again this is due to the fact that the chosen bond type affects the number of bricks that are in the assembled wall.

Plaster and the use of an additive round out the major deviations on the cost of the wall from the base case amount.

Variable	**Spearman ρ**	**Prob>| ρ |**
Transportation of bricks	0.7852	<.0001
Bond type	-0.5338	<.0001
Plaster	0.2111	<.0001
Additive	-0.0869	<.0001

Table 5.6 Spearman ρ values and p-values for variables affecting red bricks' functional unit cost

The spearman ρ coefficients from the dynamic simulation demonstrate the same ordering of the variables (Table 5.6) and the transportation of bricks and the bond type have the largest affect on the cost of the functional unit.

5.1.3 Sensitivity analysis: CSEBs

Energy sensitivity

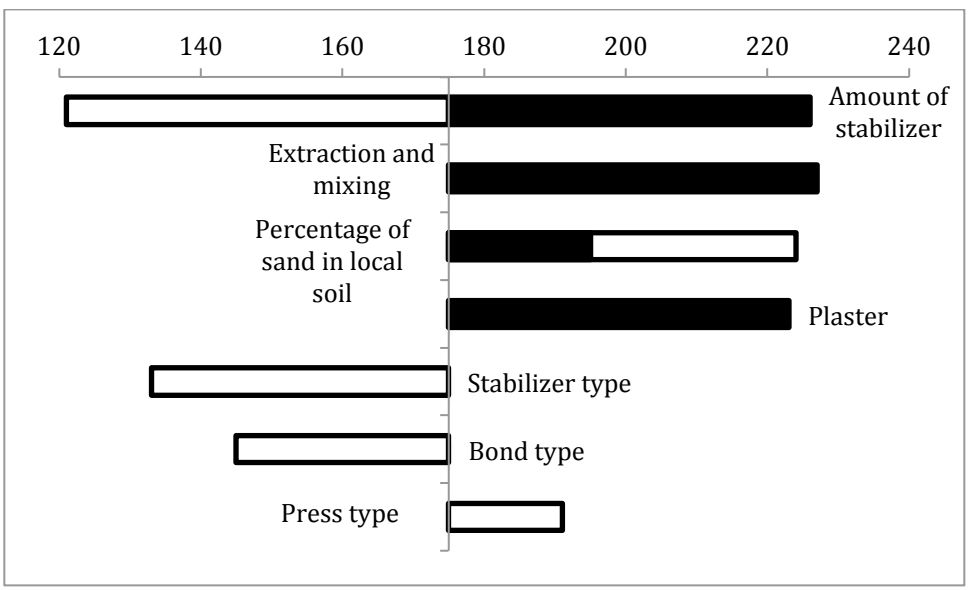


Figure 5.7 Embodied energy (MJ) sensitivity of CSEBs

Figure 5.7 shows that the amount of stabilizer has the biggest impact on the deviation from the base case embodied energy for CSEBs, with 10% stabilizer as the high point and 4% stabilizer as the low point (and 7% as the base case). The production of cement is very energy intensive due to the high temperatures required to convert calcium carbonate to calcium oxide and carbon dioxide.

Use of a tractor for soil extraction and soil-mix preparation has the next biggest effect on the sensitivity analysis, followed by the percentage of sand in the local soil (which corresponds to the local soil composition). The base case has 50% sand in the local soil (with the remaining half of the soil comprised of clay, silt, and gravel). The analysis considers a low value of 30% of sand in the soil and a high value of 70% sand in the local soil. Any components that need to be added to achieve the ideal composition of 50% sand in the local soil require transportation by truck to the site, and are assumed to be excavated mechanically in industrialized processes. Therefore, the base case has the lowest energy, 70% sand in the local soil raises the embodied energy to the next point on the plot, and 30% sand in the local soil raises it even further.

Plaster has the next biggest effect, which is understandable considering cement (or stabilizer) is one of two components of plaster, the other being sand. An oft touted benefit of CSEBs is that they do not require plaster due to their lack of porosity (AEI, 2013). However, it has also been reiterated by a number of informal interactions that individuals would likely plaster their homes if they were built with CSEBs to achieve a look of familiarity as well as uniformity with neighboring houses. The general aversion to change that was mimicked suggests that plaster is an important component to consider for any walling materials, regardless of any structural need to do so.

The remaining factors driving the sensitivity of the embodied energy are the identity of the stabilizer (either ordinary Portland cement (OPC) or Portland pozzolana cement (which incorporates coal fly ash from thermal power plants, decreasing the amount of calcium oxide (clinker) used in the cement), the layout of the walling assembly, and whether the press is manual or hydraulic. The press type has an impact on the energy consumption because of the requirement of additional components because of the additional compression achieved by the hydraulic press. In the base case where no additional components must be added to the soil, the

increase in energy consumption with the use of a hydraulic press is attributed solely to the need for more stabilizer.

It is important to note the effect that the bond type has on the embodied energy, as well as its effect on subsequent analyses. Although the base scenario assumes the layout is a single-course thick, it uses the length of the brick as the width of the wall. If the bricks were placed length-wise, instead, so that the width of the brick were the width of the wall, fewer bricks would be required to complete a square meter.

The dynamic simulation led to similar ordering of the Spearman ρ coefficients with a few notable exceptions (Table 5.7). The variables with the largest coefficients (absolute value) are those that involve the amount of cement in the functional unit (amount of stabilizer, use of plaster, and the stabilizer type). Next, unlike the manual sensitivity analysis, comes the bond type, followed by mixing and extraction. Relatively, press type and the composition of the local soil have smaller correlations with the embodied energy of the functional unit.

Variable	**Spearman ρ**	**Prob>| ρ |**
Amount of stabilizer	0.6044	<.0001
Plaster	0.438	<.0001
Stabilizer type	-0.3634	<.0001
Bond type	-0.3114	<.0001
Mixing and extraction	0.3074	<.0001
Press type	0.1438	<.0001
Percentage of sand in local soil	-0.0849	<.0001

Table 5.7 Spearman ρ values and p-values for variables affecting CSEBs' embodied energy

Emissions sensitivity

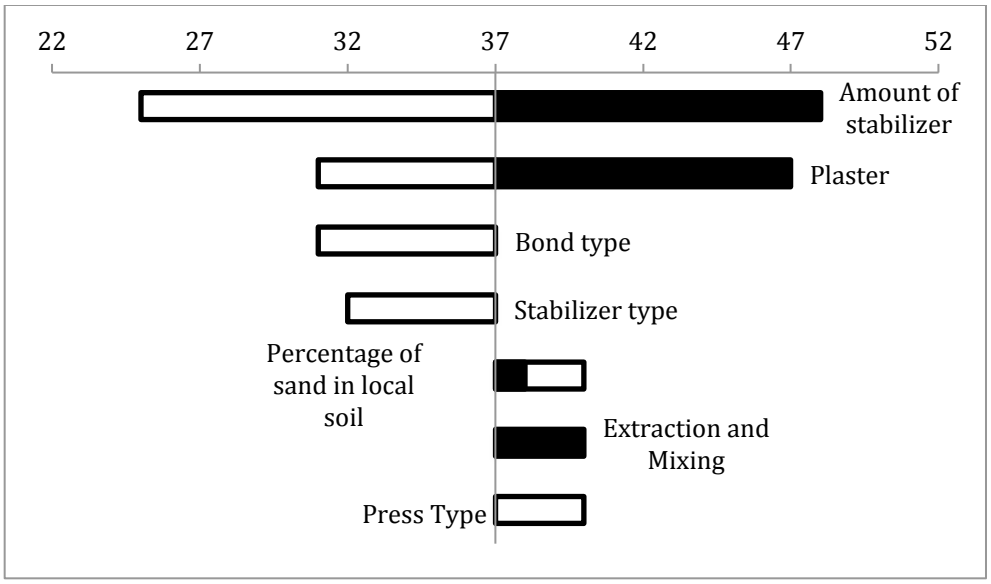


Figure 5.8 Carbon dioxide emissions (kg) sensitivity of CSEBs

The amount of stabilizer and whether or not the assembled wall is plastered also have the two highest impacts on the deviation from the base case carbon dioxide emissions, as seen in Figure 5.8. This is notable regardless of the results from the embodied energy sensitivity analysis because the carbon dioxide emissions due to cement production are based on both the burning of fuel during the calcination process and the stoichiometric conversion of calcium carbonate to calcium oxide, during which equal parts of carbon dioxide are released. The next biggest impact is the bond type, followed by the type of stabilizer used, the amount of sand in the local soil, the method of extraction and mixing, and finally by the press type used.

Table 5.8 shows the Spearman ρ values for the variables that most affect the emissions due to one square meter of walling constructed by CSEBs. The greatest drivers of carbon dioxide emissions are the same as shown in the tornado plot, while the impact of the local soil composition was insignificant, and the order of extraction and mixing and press type is reversed, with press type having half the impact that extraction and mixing has.

Variable	**Spearman ρ**	**Prob>| ρ |**
Amount of stabilizer	0.7736	<.0001
Plaster	0.4506	<.0001

Bond type	-0.3007	<.0001
Type of stabilizer	-0.1997	<.0001
Press type	0.1338	<.0001
Mixing and extraction	0.0887	<.0001

Table 5.8 Spearman ρ values and p-values for variables affecting CSEBs' embodied carbon dioxide

Land-use sensitivity

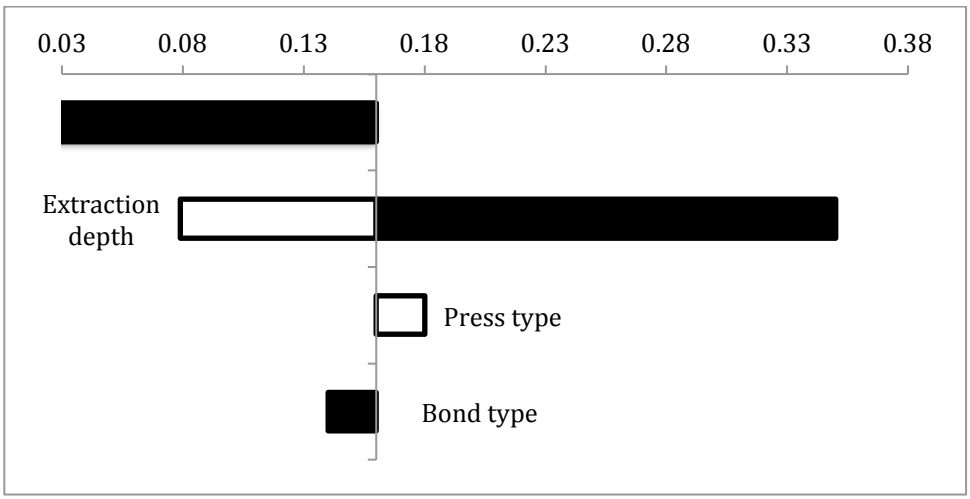


Figure 5.9 Land-use (m^2) sensitivity of CSEBs

Similar to red bricks, the land-use is most sensitive to deviations in extraction depth, followed by the press type, bond type, and amount of stabilizer, which directly affect the amount of soil that actually has to be used in the manufacture of CSEBs (Figure 5.9. The dynamic simulation yields similar results, with the effect of the bond type and the press type in reverse order. Regardless, the excavation depth has, by far, the largest impact on the land-use value (Table 5.9).

Variable	**Spearman ρ**	**Prob>| ρ |**
Excavation depth	-0.9431	<.0001
Bond type	-0.2884	<.0001
Press type	0.1424	<.0001
Amount of stabilizer	-0.0714	<.0001

Table 5.9 Spearman ρ values and p-values for variables affecting CSEBs' land-use

Cost sensitivity

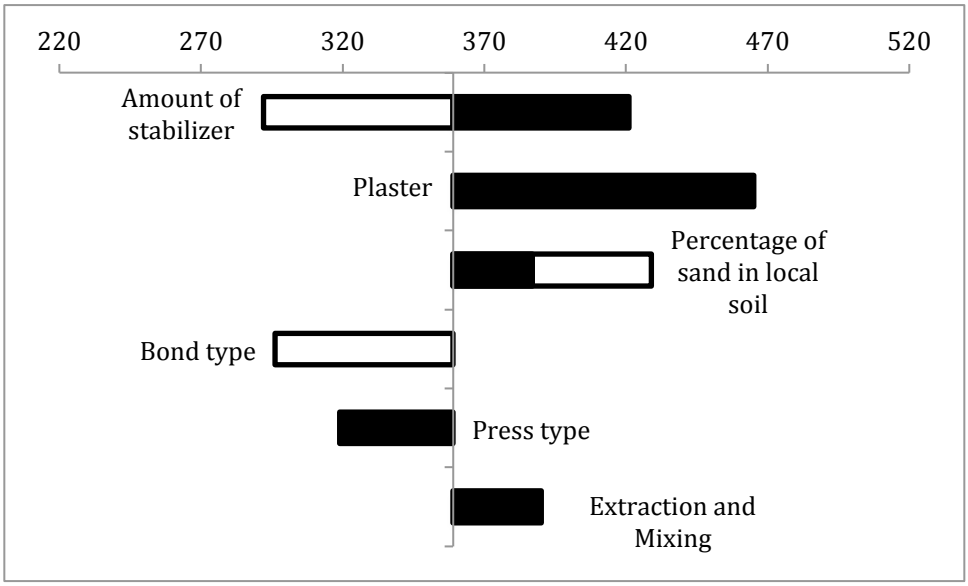


Figure 5.10 Cost (Rs) sensitivity of CSEBs

According to the manual sensitivity analysis (Figure 5.10), the largest driver of cost is the amount of stabilizer used in CSEBs, followed by whether or not the wall is plastered. Deviations in the local soil composition affect the cost due to transportation needs and the bond type again impacts the cost because of the amount of CSEBs in the functional unit. Switching to a hydraulic press from a manual press would lower the cost of a square meter of wall, presumably from the economies of scale achievable with the increased efficiency of a hydraulic press. And, finally using a tractor to extract and mix the soil raises the base cost of the functional unit because of the capital cost of purchasing a tractor and the additional cost of fueling it.

The dynamic simulation yielded Spearman coefficients that are largest for plaster and the amount of stabilizer used in the CSEBs, while the coefficient for the local soil composition is relatively lower than might be assumed from the initial sensitivity analysis. The resulting Spearman coefficients are listed in Table 5.10.

Variable	Spearman ρ	Prob>| ρ |
Plaster	0.6121	<.0001
Amount of stablizer	0.5436	<.0001
Bond type	-0.361	<.0001
Press type	-0.2297	<.0001
Percentage of sand in local soil	-0.1383	<.0001
Mixing and extraction	0.1207	<.0001

Table 5.10 Spearman ρ values and p-values for variables affecting CSEBs' functional unit cost

5.2 Synthesis of important variables

While indicating 14 variables that drive the impacts of either red bricks or CSEBs is a start in narrowing down the field from infinite possibilities, the above analyses inform the most important variables for differences. These variables will shape the hypothetical choices for case study examples in Muzaffarnagar and Hyderabad, two unique regions of India.

For red bricks, the most important variable for environmental impact is the number of bricks (and the amount of mortar) in the walling assembly, as dictated by the bond type. The use of an internal fuel can potentially decrease the energy requirements of brick manufacture, while plastering the wall has a high impact on carbon dioxide emissions. Finally, while transport of the final material has lower impacts on the embodied energy and emissions profile of red bricks (although not negligible impacts), transport does have the highest impact on the production cost of both the assembled wall and the individual red bricks. Using the more efficient VSBK instead of FCBTKs also has a positive impact on environmental concerns. The variables affecting CSEBs are substantially narrowed down following sensitivity analysis. The amount of stabilizer, stabilizer type, and use of plaster are the main drivers of environmental impact along with bond type. In terms of cost, press type, local soil composition, and the use of a tractor for extraction and mixing are also important. For both red bricks and CSEBs, the main driver of land-use is the excavation depth.

5.3 Geographic Comparison

Three regions were chosen to look at the geographic effects on the environmental and economic profiles of either material: Muzaffarnagar, Uttar Pradesh, Hyderabad, Andhra Pradesh, and Nagpur, Maharashtra. Each of these regions is characterized by a different dominant soil type and differing distances from the nearest industrial red brick production sites. In terms of soil composition, the predominant soil type in each region was considered and the high, medium, and low values of the estimated ranges of the sand composition is considered. It is important to note that the soil breakdown in Table 3.4 is based on the soil texture triangle in Figure 3.3, and only includes sand, clay, and silt, while the analysis of soil composition for CSEB production looks at the percentage of sand, clay, silt, and gravel in the soil. Therefore, when including the ranges for sand composition in the model, the values from the table were converted to include gravel.

5.3.1 Muzaffarnagar

Muzaffarnagar, as mentioned previously, is an industrial city with large-scale red brick production. Thus red bricks produced there need little transportation to their final destination. Additionally, the soil composition is mainly alluvial, which corresponds to a wide range of possible sand compositions, as the sand can range from 35% - 80% of the total soil composition.

5.3.2 Hyderabad

Hyderabad is the capital city of Andhra Pradesh in the South of India. Greater Hyderabad covers an area of 650 km^2, making it one of the largest metropolitan regions in India (Greater Hyderabad municipal corporation). The primary soil type in the region is red soil, corresponding to a sand composition of 20% - 45%. For the purpose of modeling the comparative environmental and economic impacts of red brick and CSEB use, red bricks were assumed to travel a conservative average of 350 km to the construction site.

5.3.3 Nagpur

The Nagpur region of Maharashtra is approximately 10,000 km^2, including rural villages and the urban region of Nagpur itself. The main soil type in this region is a clayey black soil, which

corresponds to a sand composition of 10% - 40%. Red bricks were conservatively assumed to travel 150 km to the construction site.

5.3.4 Comparison of red bricks and CSEBs

As seen in Figure 5.11, in general CSEBs have a lower median embodied energy than red bricks. There is also a further spread in the possible values for embodied energy for red bricks. However, the fact that the two plots overlap indicate that there is the possibility that certain decisions regarding red bricks could lead to lower embodied energy values than certain decisions regarding the production of a wall with CSEBs. Change in transportation distance for finished red bricks has more of an impact on the embodied energy of red bricks than does the corresponding change in local soil composition on the embodied energy of CSEBs.

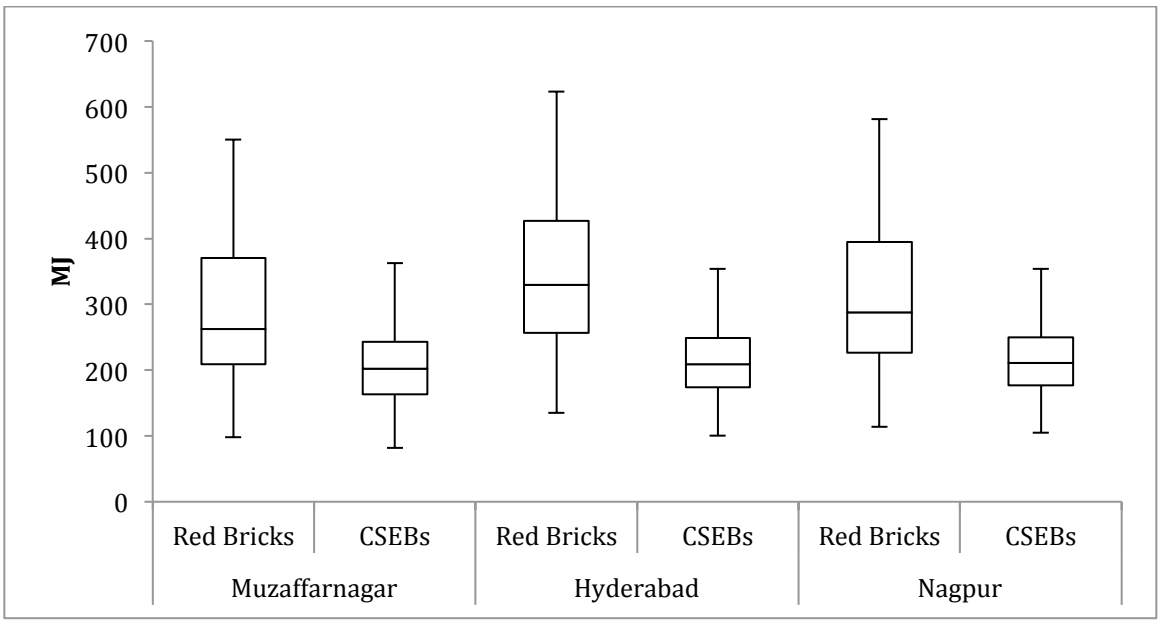


Figure 5.11 Possible embodied energy values in MJ for red bricks and CSEBs

Figure 5.12 shows that the median value of embodied carbon dioxide in CSEBs is actually higher than red bricks in Muzaffaranagar, though not by much. It is essentially equal in Nagpur, and the

emissions in Hyderabad are higher for red bricks than CSEBs. Interestingly, the values of embodied carbon dioxide emissions are much closer between materials than the values of embodied energy. This is likely due to the carbon dioxide released during the production of cement, which is a component of CSEBs, highlighting the fact that, in this case, embodied energy is not a perfect proxy for carbon dioxide production of these materials. In each location, there is significant overlap between the plots of each material, which underscores the need for further exploration of individual scenarios.

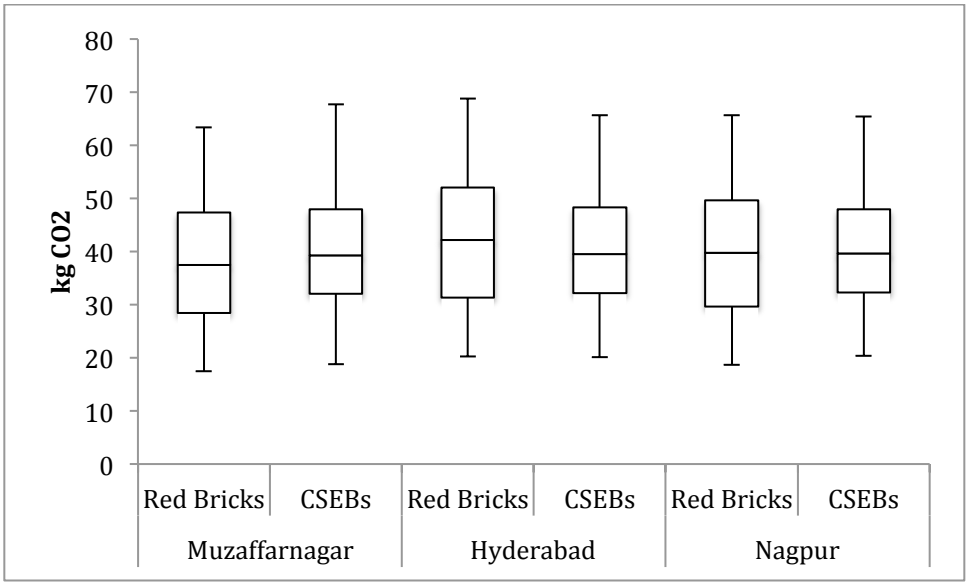


Figure 5.12 Possible embodied carbon emissions in kg for red bricks and CSEBs

Figure 5.13 shows the possible land-use values for red bricks and CSEBs. The median value for each is similar, with both having large spreads of possible values. Additionally the values for land-use possibilities in each of the locations is exactly the same since the model calculates the land-use based on the amount of material that goes into the production of the blocks, which should not change based on location.

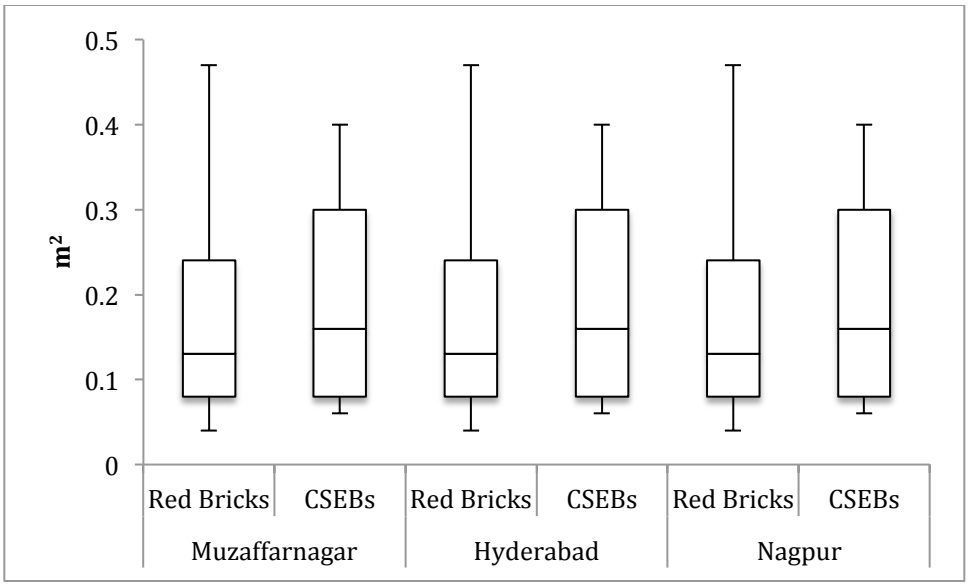


Figure 5.13 Possible land-use in m^2 due to production of red bricks and CSEBs

As seen in Figure 5.14, red bricks have a lower median cost per functional unit than CSEBs in Muzaffarnagar, a slightly higher median cost in Nagpur, and a significantly higher cost in Hyderabad. In each case, however, there is still overlap between red bricks and CSEBs indicating the potential for either material to lead to a lower cost per square meter of walling. However, Figure 5.15 shows a different picture when considering the cost on a per brick basis. The cost of red bricks will always be lower than the cost of CSEBs (given the technologies and conditions considered in this analysis) in Muzaffarnagar, while in Nagpur there is some overlap between the per unit cost of red bricks and CSEBs. Hyderabad shows the greatest overlap between both materials, as well as the highest per unit cost for red bricks by far. Interestingly, Muzaffarnagar has the lowest per-brick cost for CSEBs, followed by Hyderabad and finally Nagpur. Still, the changes in the median price and overall shifts of the spreads are fairly small, demonstrating a greater relative effect due to the travel distance of red bricks versus variations in the local soil composition. Furthermore, it is interesting to note how little variation there is in the production cost of red bricks versus the variations seen in CSEBs.

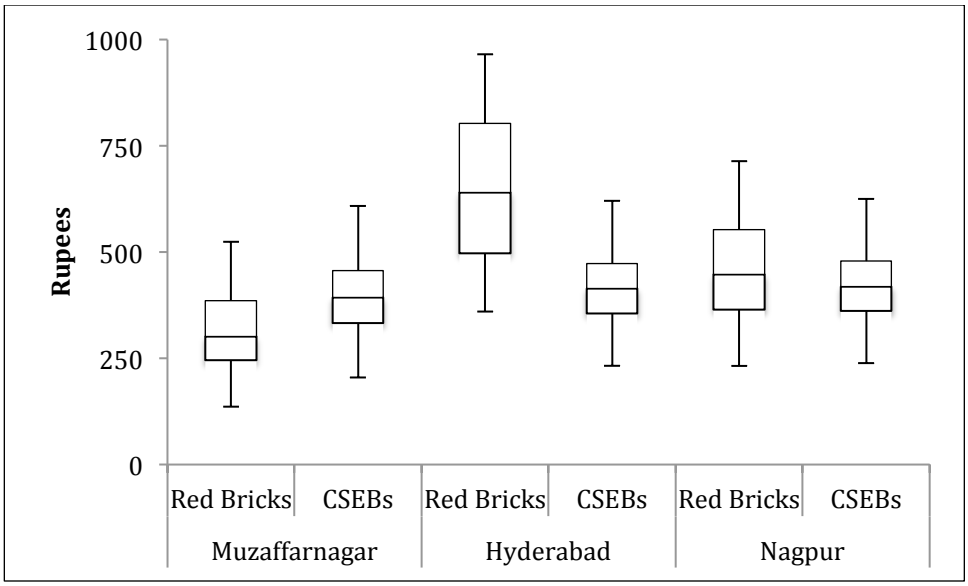


Figure 5.14 Possible cost per meter square of walling in rupees for red bricks and CSEBs

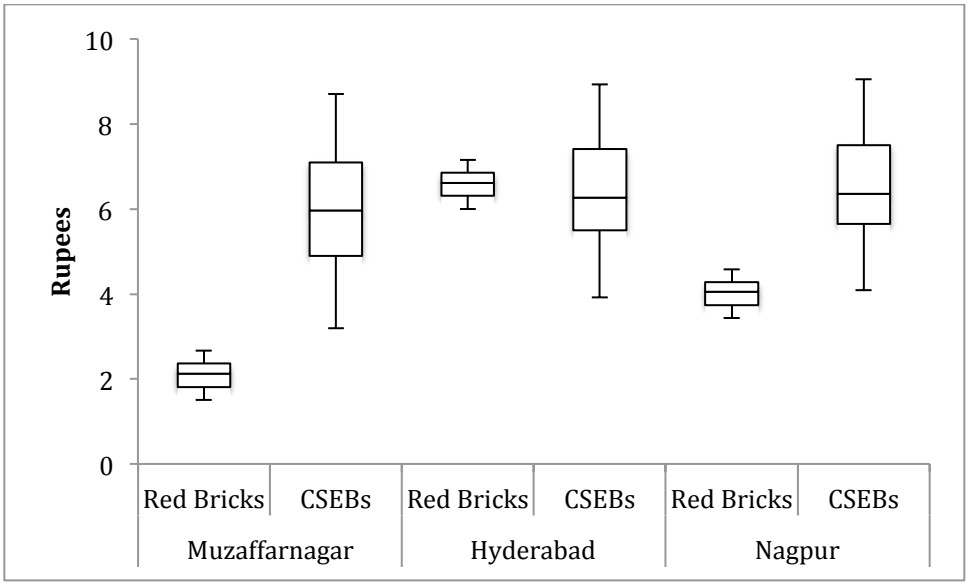
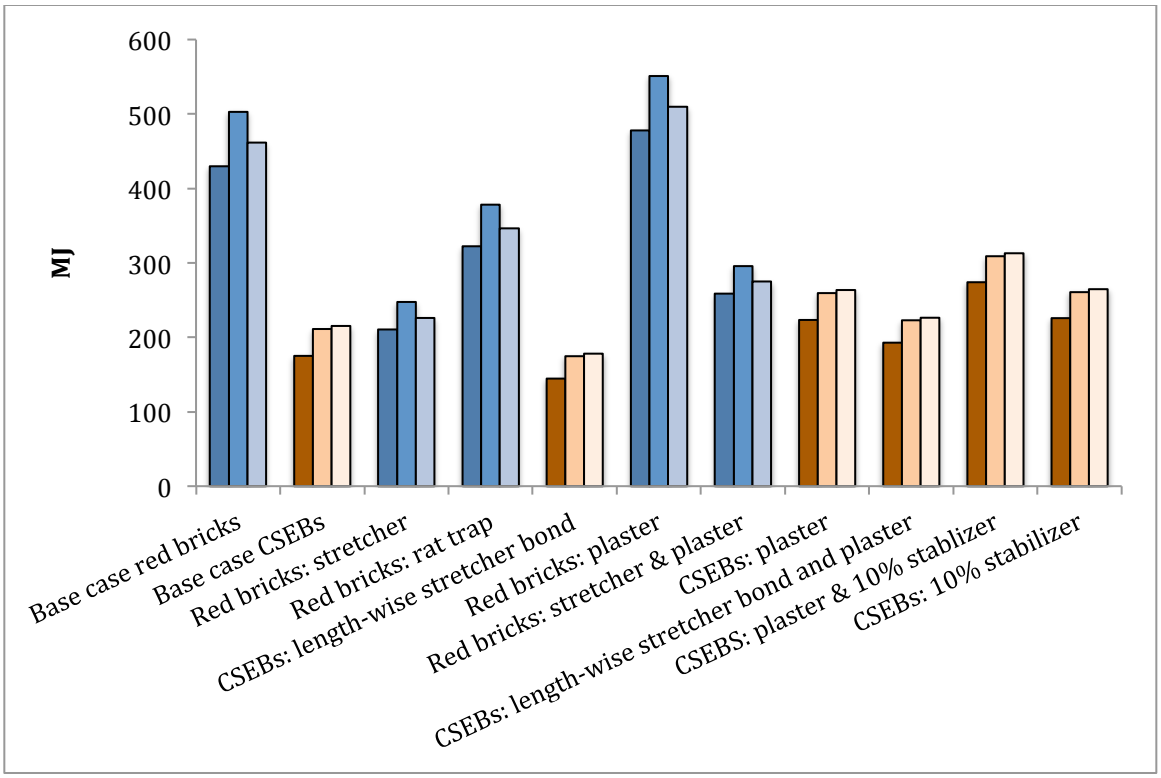


Figure 5.15 Possible cost per masonry unit (brick) in rupees for red bricks and CSEBs

5.4 Scenario analysis

21 different scenarios were considered for red bricks and CSEBs in each location to describe situations that cover the areas of overlap in the box-and-whisker plots. In each of the subsequent

plots, the base case for red bricks and CSEBs is highlighted and the description for each scenario indicates the changes from the base case situation for the material in question.



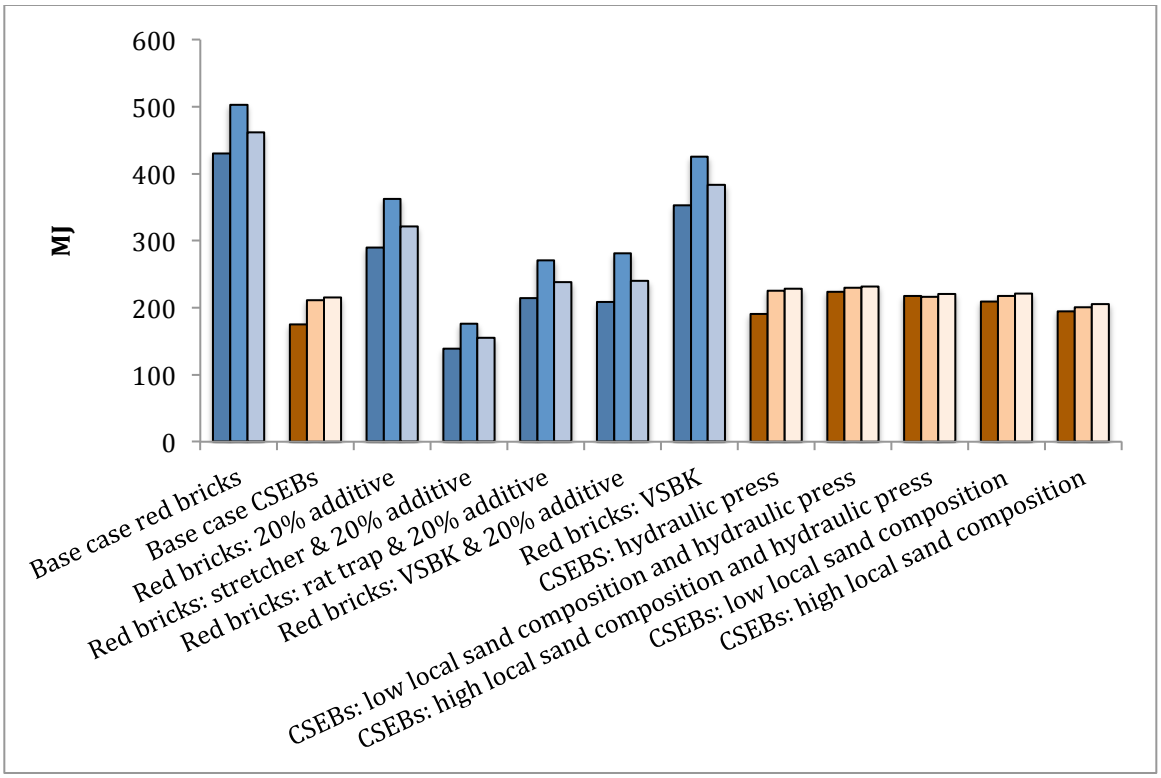
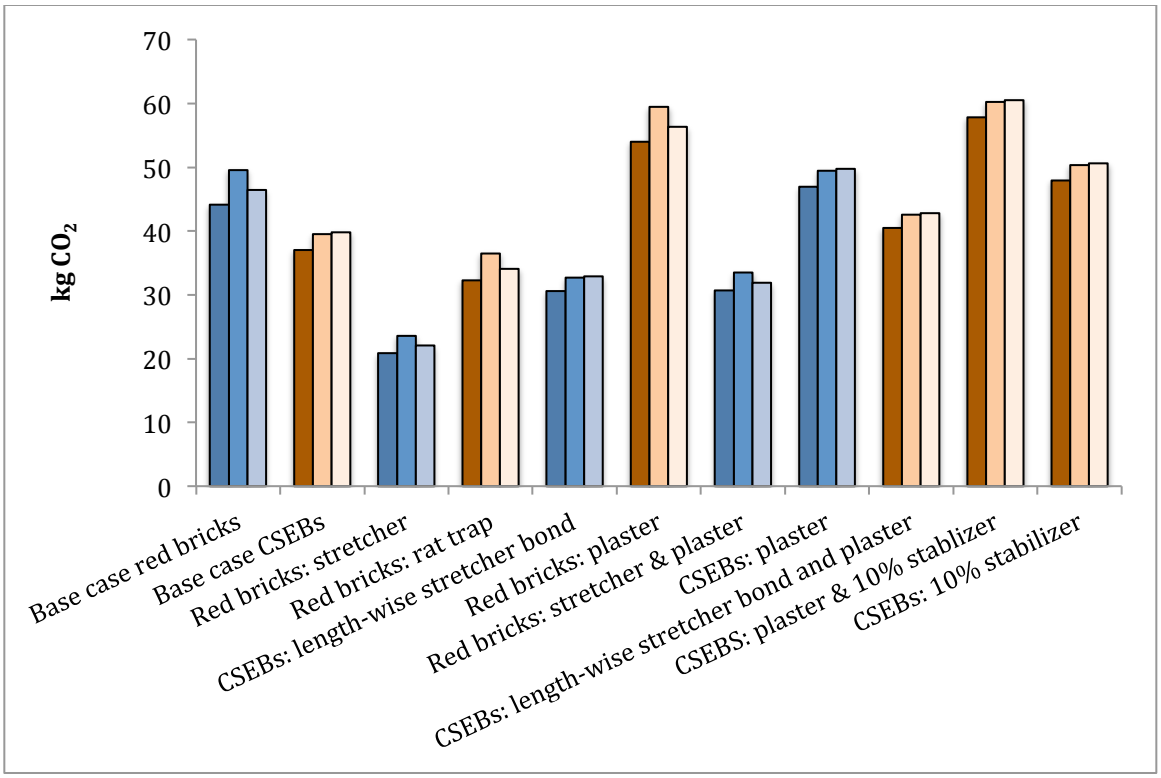


Figure 5.16 Embodied energy scenarios for red bricks and CSEBs in Muzaffarnagar, Hyderabad, and Nagpur in that order

As seen in Figure 5.16, the base case for red bricks entails a much higher embodied energy than the base case for CSEBs in each location. Notably, the difference between the values for each scenario in different locations is not as drastic as the changes between scenarios themselves, demonstrating the importance of production choices over the geographic region in terms of embodied energy. However, there are scenarios that would actually put red bricks on par with CSEBs. Change in the bond type of either material decreases the overall embodied energy of the walling system.

Use of plaster on either wall assembly drives up the embodied energy significantly, but the CSEB embodied energy still remains below the base embodied energy for red bricks. Use of more stabilizer also has a noticeable impact on the embodied energy of CSEBs. Including internal fuel in red bricks significantly decreases the embodied energy, particularly when compounded with the use of fewer bricks in alternative bond formations (safety not withstanding), and the use of a VSBK has a preferable effect on the embodied energy of the wall, but not as great as the use of internal fuel. Finally, the use of a hydraulic press and the consideration of variations in the local soil composition have minimal impacts on the embodied energy of CSEBs.



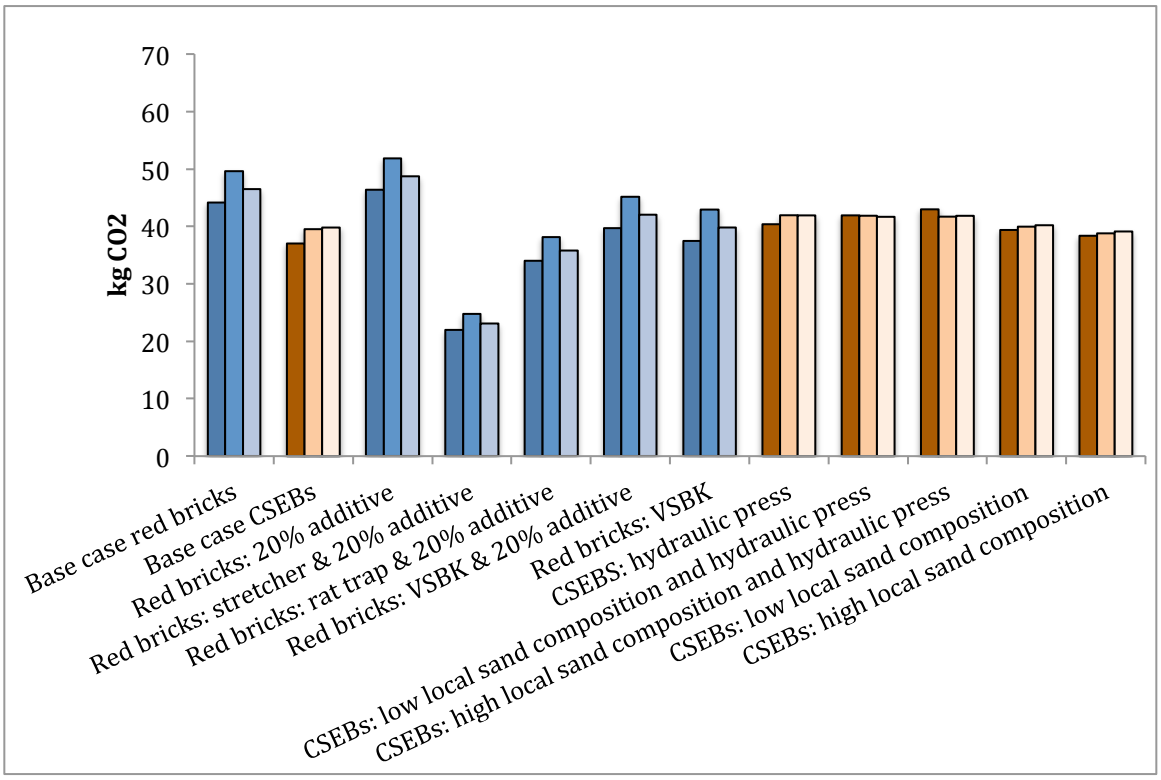


Figure 5.17 Embodied carbon dioxide scenarios for red bricks and CSEBs for Muzaffaranagar, Hyderabad, and Nagpur (in that order)

In the case of embodied carbon dioxide emissions, Figure 5.17 shows that the base case for red bricks and CSEBs are much closer than the embodied energy values. This is due to the use of cement in CSEBs. Use of a stretcher or rat trap bond would drop the emissions profile of red bricks below the CSEB base case, while the change in orientation of bricks in the CSEB bond layout also drops the emissions profile.

Plaster use raises the emissions profiles in both materials in each location above the base case of either. Plaster on a red brick stretcher bond keeps the emissions profile of red bricks below that of the base CSEB case. Using more stabilizer with or without plaster in CSEBs raises the emissions above the profile of the red bricks base case.

The use of boiler ash as an additive actually drives up the emissions relative to the base case because of the extra electrical energy used in the grinding of the ash. As more is known about the relationship between burning internal fuel versus external fuel in the kiln, the relationship between the use of additives in bricks and carbon dioxide emissions will be better understood than presented here. The use of a VSBK lowers the emissions profile of red bricks.

Finally, changes in the type of press used, or the variation in the local soil composition within the bounds dictated by the overall soil characterization, have little effect on the emissions profile of CSEBs, especially when considering the effects of other scenarios.

Analysis of changes in land-use (Figure 5.18) corroborate earlier findings that the main driver is the number of bricks in the functional unit (and the excavation depth, which was excluded from this analysis because it is so dependent on local geography that it is not a decision that can be made a priori.) As expected, these values do not change based on geographic region for either material.

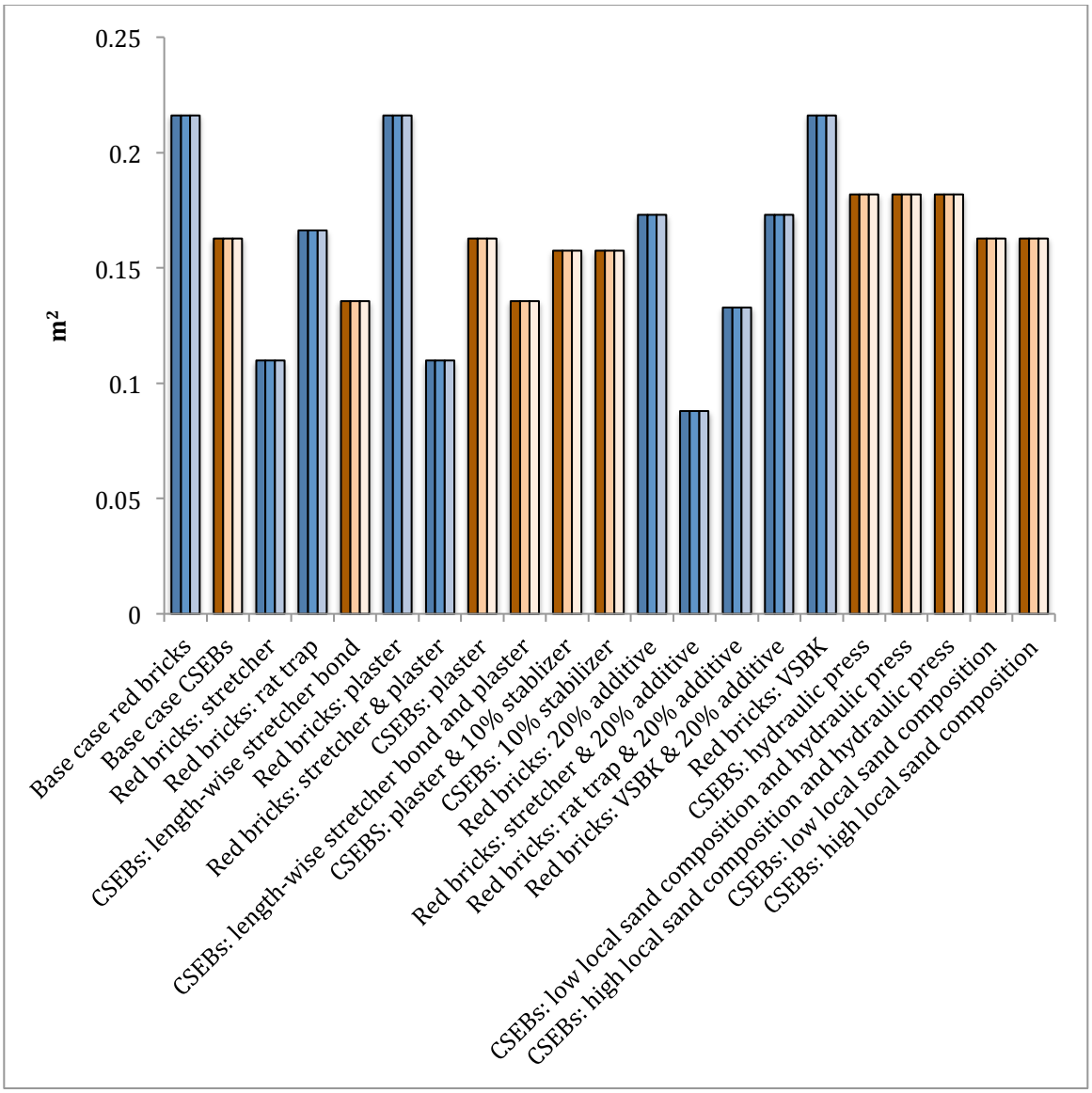


Figure 5.18 Land-use scenarios for red bricks and CSEBs in Muzaffarnagar, Hyderabad, and Nagpur in that order

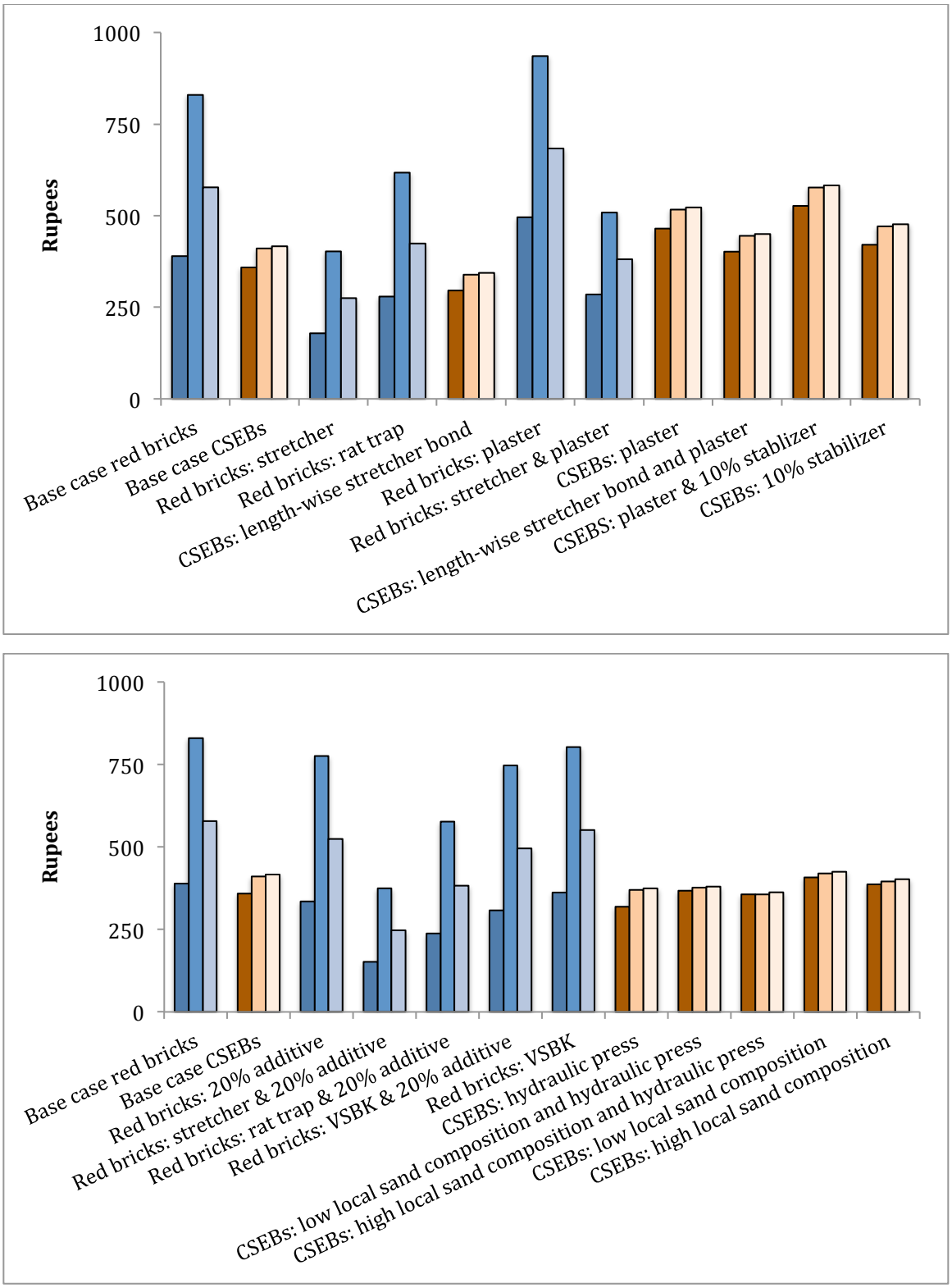


Figure 5.19 Functional unit cost scenarios for red bricks and CSEBs in Muzaffarnagar, Hyderabad, and Nagpur in that order

The functional unit costs for both red bricks and CSEBs in Muzaffarnagar are very close, and it is actually cheaper to produce a wall of CSEBs than bricks (Figure 5.19), while much bigger differences are seen between the costs of either material in Hyderabad and Nagpur. Additionally, the cost of CSEBs in Nagpur is slightly higher than the cost of CSEBs in Hyderabad.

As expected, the use of bonds that require fewer bricks drive down the functional unit costs of either material, while the use of plaster causes an increase in cost. This increase in cost is not as drastic as the increase in the environmental parameters seen with the introduction of plaster to the walling system. Additional stabilizer increases the cost of CSEBs in each location slightly.

Use of an internal fuel decreases the cost slightly, but not as much as the subsequent analysis of bond types that require fewer bricks. Finally, the use of a hydraulic press lowers the cost of CSEBs a bit, while changes in soil composition have smaller changes overall. There is, however, a slightly bigger jump when sand composition changes in Muzaffarnagar. This is due to the rather large range of sand composition found in alluvial soil.

The results seen in Figure 5.20 show the variations in the unit cost of bricks. Thus scenarios that vary only in how the wall is assembled do not show changes in the per brick cost; only scenarios in which the production of the bricks themselves vary demonstrate these changes. As concluded in the box-and-whisker plot for the cost per individual masonry unit (Figure 5.15), there is absolutely no overlap between the scenarios in Muzaffarnagar in terms of the individual brick costs. In fact, the per brick cost for red bricks in Muzaffarnagar hovers around 2 rupees, while the cost for each CSEB varies more, but still stays above 5 rupees (except for the scenario that uses a hydraulic press and has no other deviations from the base case).

In Nagpur, the cost of red brick production stays around 4.3 rupees, while the price of CSEB production stays above 5.8 rupees, reaching above 8 rupees in the case where additional stabilizer is used in the soil mix. Finally, in Hyderabad, the cost of red brick production nears the price of CSEB production in many cases. The use of a hydraulic press for CSEBs perhaps becomes most important in this region because it allows the unit cost of CSEBs to be less than the unit cost of red bricks.

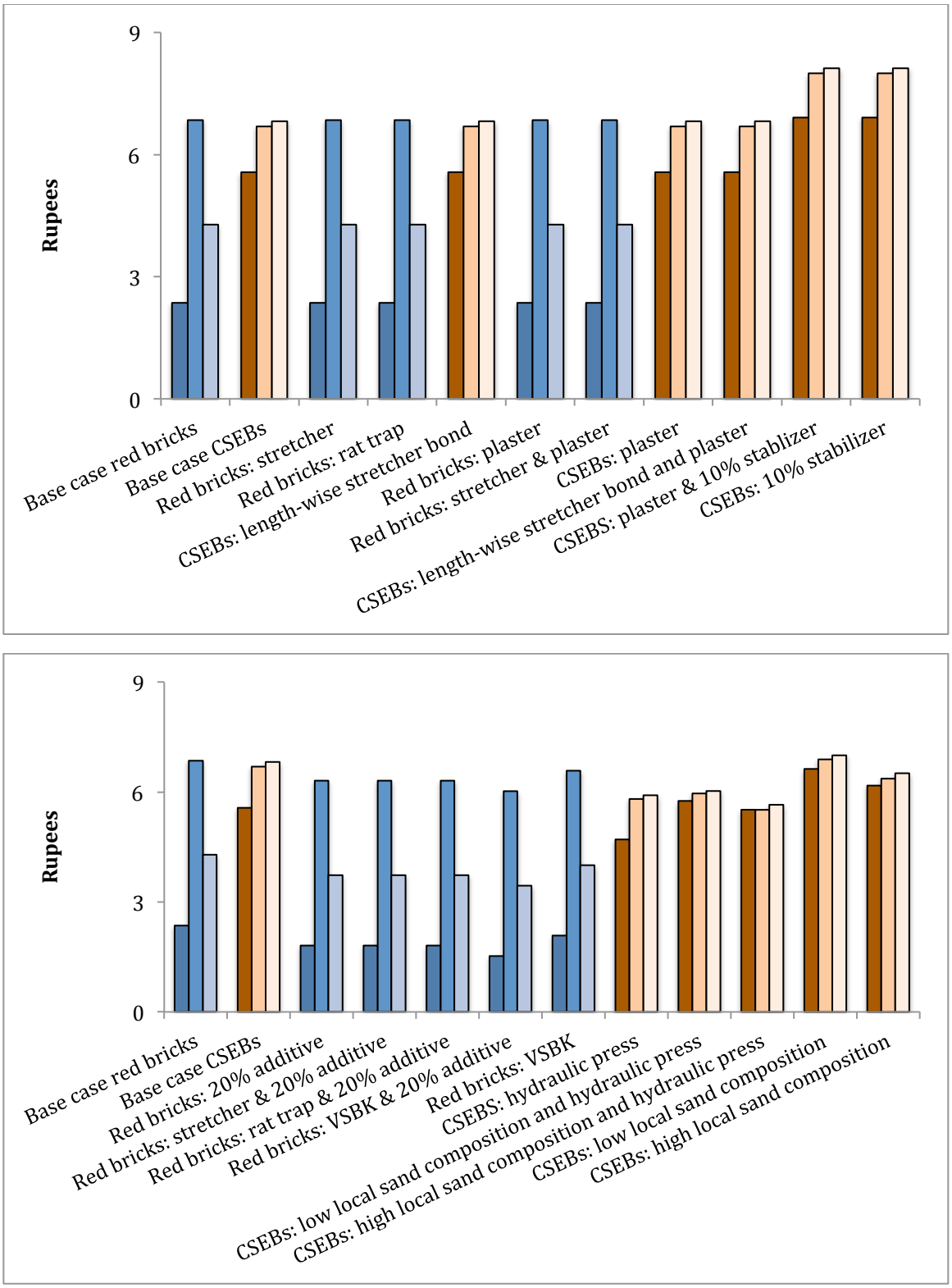


Figure 5.20 Per brick cost scenarios for red bricks and CSEBs in Muzaffarnagar, Hyderabad, and Nagpur in that order

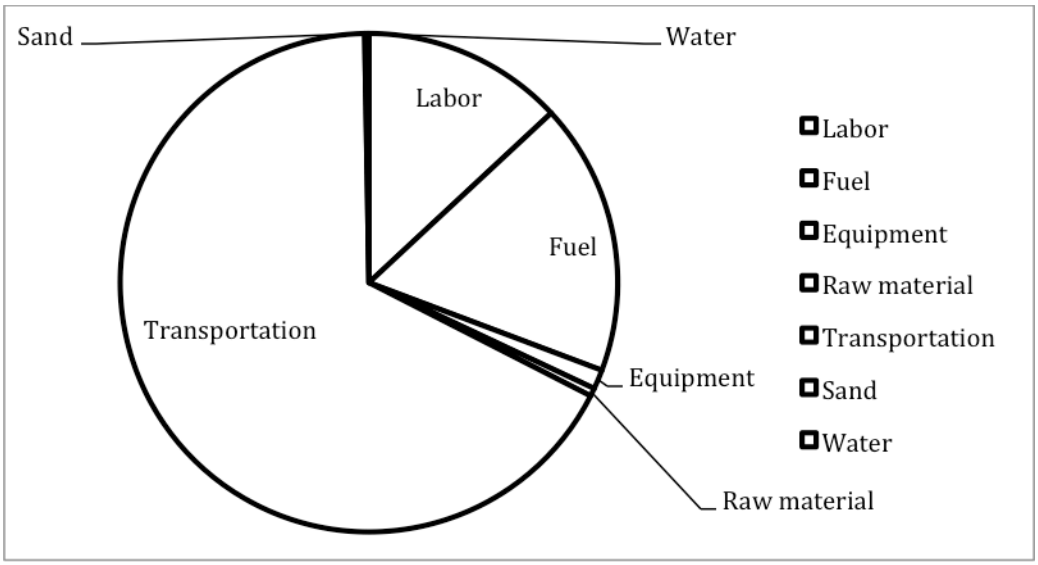


Figure 5.21 Cost breakdown of red brick production in Hyderabad (categories listed clockwise from labor)

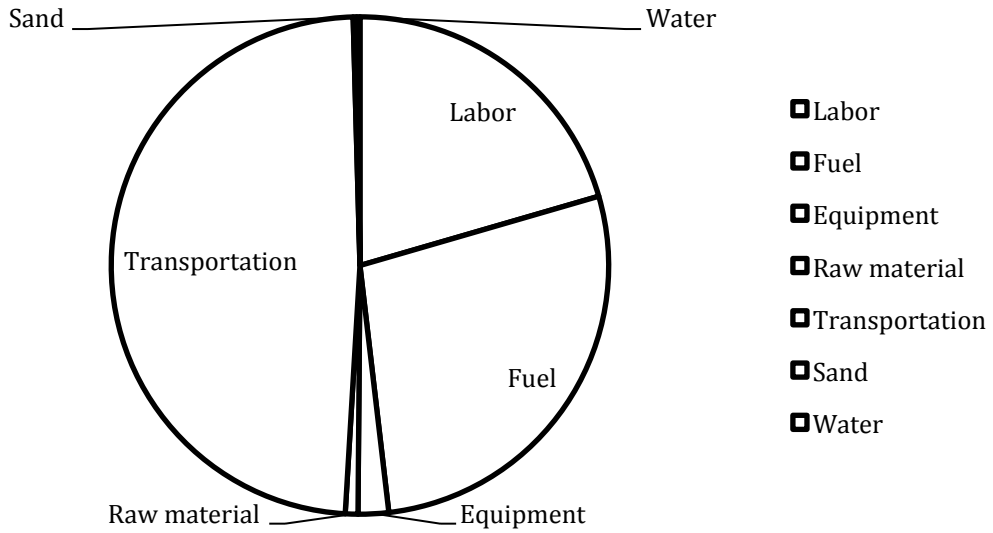


Figure 5.22 Cost breakdown of red brick production in Nagpur (categories listed clockwise from labor)

Figure 5.21 and Figure 5.22 show the cost breakdown of red brick production in Hyderabad and Nagpur now that transportation of the finished product has been added to the equation. As seen, transportation accounts for more than half of the cost in Hyderabad and about half of the cost in Nagpur, further accounting for the jump in cost per brick and per functional unit that is seen above.

5.5 Preliminary conclusions

In terms of embodied energy and carbon dioxide, the transportation of finished red bricks affects the median value for both indicators, as seen in the differences among locations. But is not the largest driving force in the absolute values for either in terms of red bricks. Similarly the difference across regions in terms of CSEB embodied energy is small in comparison to the changes due to different scenarios. For both materials the wall structure itself has a major impact on the environmental impact. Plaster is another major driver of the environmental impact of the wall. Finally, improved kiln efficiency and optimization of internal fuel use could have positive results on the environmental impact of red bricks.

While land-use is an important indicator, the tradeoff between red bricks and CSEBs is nominal and not heavily dependent on materials choice. It is instead driven by excavation practices and the thickness of a given walling assembly. As expected, because of how it is defined in this thesis, it does not differ based on geographic location.

While the local soil conditions ultimately determine whether production of either material is feasible, the composition of local soil is not the major driving factor behind changes in the environmental and economic impact for CSEBs. Instead, what is most important is the comparison between red bricks and CSEBs, and this is ultimately driven by the production methods of either (kiln type, amount of stabilizer, and so on) for the environmental cost.

Plaster increases the economic cost of an assembled wall of either material, as does the use of more stabilizer in CSEBs. Interestingly, the use of a hydraulic press actually has a favorable impact on the cost of individual CSEBs and the functional unit, due to the ability to achieve greater economies of scale with greater production capacity per day. Cost for both the assembled wall and individual red bricks is heavily dependent on the transportation distance, as seen by both the drastic increase in cost in Hyderabad versus Muzaffarnagar and by the small variation in cost in all three locations across the different scenarios (underscoring transportation as a key driver).

The transportation of red bricks determines whether or not the per brick cost is competitive with the unit cost of CSEBs. As seen in Figure 5.23, the local soil composition does affect the cost

with alluvial soil leading to a lower cost than the others (except for desert soil) by about 20%. Figure 5.24 shows the distance the red bricks have to travel in order for the unit cost to be equal to or greater than the unit cost of CSEBs given the median value of the local soil composition. Some of these scenarios are unrealistic, as most regions with alluvial soil have red brick production for instance. In general, red bricks need to travel *at least* 300 km for the unit cost of the materials to be on par with each other. On the other hand, the cost effectiveness of a CSEB walling assembly can be, and usually is, competitive regardless of the unit cost of the red bricks as seen in the above analyses.

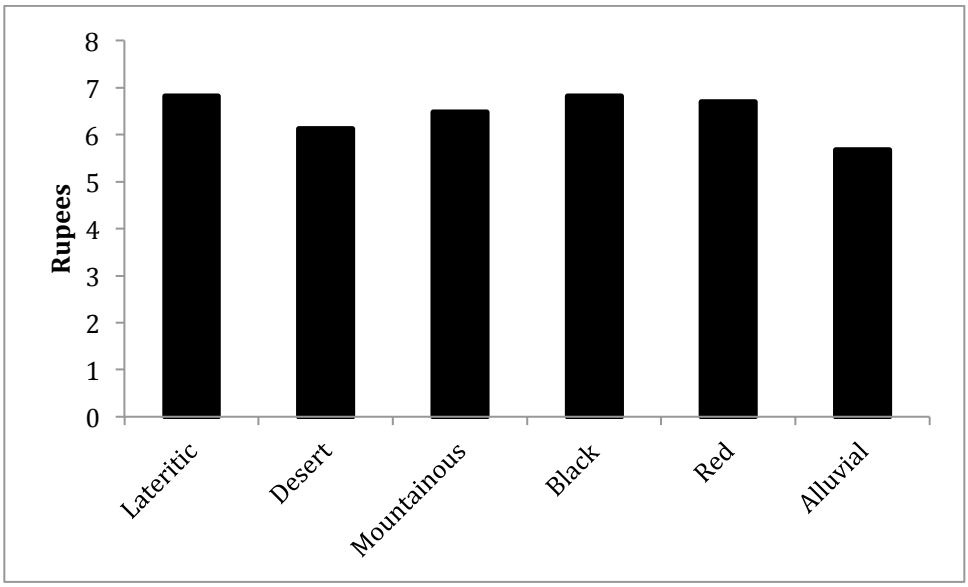


Figure 5.23 Unit economic cost for CSEBs based on median sand composition of local soil type

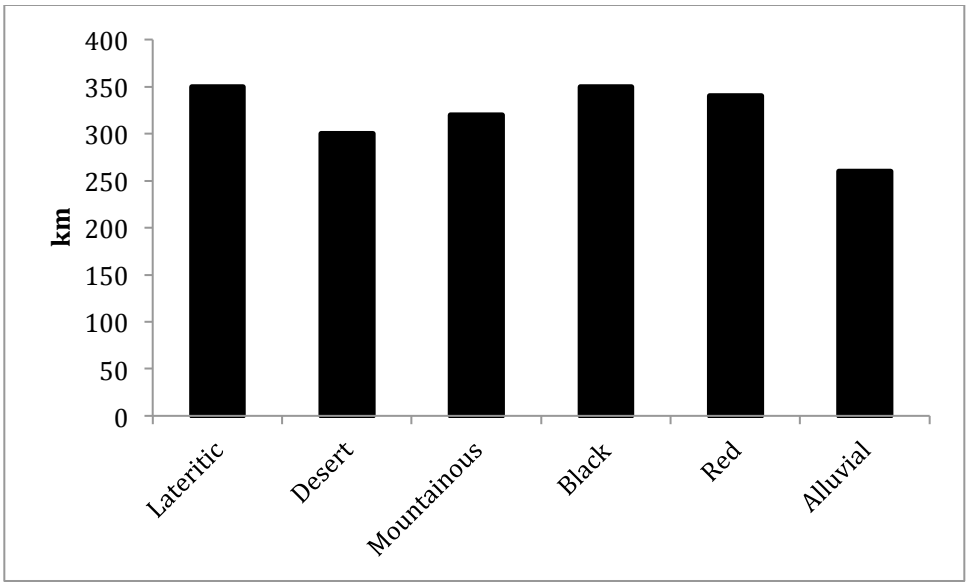


Figure 5.24 Distance red bricks must travel for unit price of CSEBs to be competitive based on median sand composition of local soil type

6 CONCLUSIONS

Taking into account the various production choices that can affect the environmental and economic impact of masonry materials leads to a complicated analysis that requires knowledge about local conditions and practices in order to make choices about the optimal material. However, there are certain conclusions that can be drawn in order to successfully introduce new, alternative materials into segments of the Indian market that will be viable economically while also decreasing the environmental footprint of construction activities.

This thesis looks at two materials: traditional fired clay bricks (red bricks) and CSEBs, focusing on production steps and geographic considerations. Process-based models for each were developed to consider these different levers and to allow for a bottom-up analysis of environmental and economic impacts (as opposed to taking a finished product and working backward through the specifics of its production). Using these models and simulation data allowed for analysis of the most important variables in the impacts of each material, as well as for comparison of the two in different locations.

The original question this thesis sought to answer was: Which are more environmentally and economically beneficial? Red bricks or CSEBs? As is so often the case when there is any

introduction of variation into an analysis, the answer is: It depends. It depends on geographic location and soil composition. It depends on production choices in the fabrication of the masonry materials themselves. And it depends on construction decisions regarding the bond layout of the assembled wall. However, this thesis concludes that there are a handful of key components that are most important to the answer:

- The local soil composition has an effect on the ability to make either material. Red brick production is best in regions with alluvial soil and that is where industrial production is highly established. Transportation of finished red bricks has the highest impact on cost. In fact, only in regions where the red bricks must travel long distances by truck are CSEBs cost competitive on a per-unit basis. On a functional unit basis, however, CSEBs are cost effective even in areas where red bricks are made, as long as structural minimums for building are enforced (ie where builders definitely use English bond formations for red bricks).
- Plaster use itself has a significant impact on both environmental and economic impact. Alternatives to cement and sand based plasters (and mortar) could improve the impacts in both areas.
- In general, the environmental impact of CSEBs' base case scenario is lower than that of red bricks. It is therefore worth pursuing development of best practices in order to make them economically viable while maintaining characteristics that keep them environmentally competitive.
- Use of a hydraulic press, operating at full capacity lowers the per unit cost of CSEBs, suggesting that it is worthwhile to develop the technology at an industrial scale, as opposed to the production of bricks for an individual project. The use of a hydraulic press does increase the environmental footprint of CSEBs because of the need of extra soil because of the additional compression achieved but not so much that the environmental benefits of these materials are lost entirely.
- The cement used in CSEBs has a significant impact on the embodied carbon dioxide emissions of these materials, and research into materials that can serve as binders that do not chemically release as much carbon dioxide would be beneficial. As seen in the cost breakdowns, stabilizer is a substantial part of the cost of CSEBs, and finding a

replacement that required little to no firing (and therefore minimal fuel, which is a major component of the cost of red bricks) is a worthwhile research endeavor.

The preceding analysis suggests that there is future work in the development of materials that serve as viable alternatives to the ubiquitous red brick in the Indian context while developing models that can be tuned to analyze the environmental impact of materials given changes in geography or production method. Further data collection on the ground is required to have a more comprehensive picture of the fuel consumption in these industries. While the only firing that affects CSEBs is that in the production of cement, which is a heavily regulated and standardized industry, the firing of red bricks is very inconsistent. Fuel can actually be defined as anything that will burn. Therefore while this thesis looks at coal as a reference fuel, further understanding of the types of fuels used and their environmental impacts is a crucial next step.

Transportation distance has a large impact on the production cost of individual red bricks, which are typically less costly than CSEBs. However, even in regions where red bricks do not have to travel to their final destination (like Muzaffarnagar), the cost for an assembled CSEB wall is on par with or less than a structurally sound red brick wall. Therefore, CSEBs are cost competitive as long as the purchasers are able to make decisions on a wall-basis as opposed to a per-brick basis. This means that building projects need to be done by contractors or developers who are analyzing their bottom-line more long-term than individual builders who purchase bricks when they can afford them. On the flip side, more education about long-term financial strategies, access to savings instruments, and financing options would better allow even the self builder to see the economic benefit to purchasing larger masonry units with a greater per-unit cost but a lower assembled cost. As suggested by the stakeholder analysis, NGOs that are on the ground are the best positioned to influence and enable the adoption of new materials and it is important that future work further interfaces with NGOs to ensure that they have the information they need to make the best decisions.

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Appendix A - Underlying data for both models

Category of measurement	Compound	Value	Unit	Notes
Calorific value	Diesel fuel	42.9	MJ / kg	The Engineering ToolBox
Components	Cement in mortar	1	kg	Maithel et al
Components	Cement in plaster	11.6	kg / m^2	Maithel et al (2011)
Components	Sand in mortar	5.33	kg	Maithel et al
Components	Sand in plaster	49.4	kg / m2	Maithel et al
Daily capacity	Hydraulic press	2500	bricks	AEI
Daily capacity	Manual press	850	bricks	AEI
Density	Cement	1522	kg / m3	The Engineering ToolBox
Density	Clay	960	kg / m3	The Engineering ToolBox
Density	Diesel fuel	837	kg / m3	The Engineering ToolBox
Density	Fly ash	721	kg / m3	The Engineering ToolBox
Density	Gravel	1282	kg / m3	The Engineering ToolBox
Density	Lime	481	kg / m3	The Engineering ToolBox
Density	Mortar	2300	kg / m3	The Engineering ToolBox
Density	Sand	1200	kg / m3	The Engineering ToolBox
Density	Silt	2798	kg / m3	AgriInfo.in
Density	Water	1000	kg / m3	Known conversion
Economic discount factor		20%		This conservative discount factor was used to take into account the high cost of capital in India and the relatively unpopular idea of financing.
Embodied emissions	Sand	0.00229	kg / kg	EcoInvent
Embodied energy	Diesel truck	0.7254	MJ/ton-km	Calculated based on inputs
Embodied energy	Fly ash (grinding)	0.05	kWh / kg	Joergensen
Embodied Energy	Mortar	0.70863 9494	MJ / kg	Calculated based on inputs
Embodied Energy	Mortar	1629.87 0837	MJ / m^3	Calculated based on inputs
Embodied energy	OPC	4.2	MJ / kg	EcoInvent

Embodied Energy	Plaster	46.49584	MJ / m^2	Calculated based on inputs
Embodied energy	PPC	2.87	MJ / kg	Calculated based on values for cement components and fly ash processing
Embodied energy	Sand	0.0536	MJ / kWh	EcoInvent
Emissions factor	Diesel fuel	2.69	kg co2 / kg	The Engineering ToolBox
Emissions factor	Diesel truck	0.064872	kg CO2 / ton - km	Calculated based on values supplied by Greentech Knowledge solutions
Emissions factor	Fly ash (grinding)	0.041	kg CO2 / kg fly ash	Calculated using grid emissions conversion
Emissions factor	Mortar	0.145166777	kg CO2 / kg	Calculated based on inputs
Emissions factor	Mortar	333.8835877	kg CO2 / m^3	Calculated based on inputs
Emissions factor	OPC	0.9067	kg co2 / kg cement	EcoInvent
Emissions factor	Plaster	9.744606	kg co2 / m2	Calculated based on inputs
Emissions factor	PPC	0.76	kg co2 / kg cement	EcoInvent
Energy Density	Tractor - diesel	15	km / l	Zachau-Walker
Energy density	Truck - diesel	2.75	km / l	Greentech Knowledge Solutions correspondence
Price	Cement	5	Rs / kg	Delhi Schedule of Rates
Price	Diesel	54	Rs / liter	Greentech Knowledge Solutions correspondence
Price	Gravel	16	Rs / ft^3	Delhi schedule of rates
Price	Hydraulic press	144000		AEI
Price	Land rental / year	16.8	Rs / m2	Kisan bricks correspondence
Price	Manual press	95000		AEI
Price	Mortar	3654.15	Rs / m^3	Calculated based on inputs
Price	Plaster	95.364	Rs / m2	Calculated baed on inputs
Price	Price (good roads)	2.75	Rs / ton-km	Greentech Knowledge Solutions correspondence
Price	Price (mountains)	6	Rs / ton-km	Greentech Knowledge Solutions correspondence

Price	Sand	3	Rs / kg	Delhi Schedule of Rates
Ratio	Bulking ratio for soil from ground	1.4	m3 loose : ground	AEI
Ratio	Compression ratio for manual press	1.7		AEI
Ratio	Compression ration for hydraulic press	1.9		AEI
Wage	medium skilled	115	Rs / day	http://www.nrcaf.ernet.in/ aicrpaf/pdf/angrau.pdf
Wage	skilled	160	Rs / day	http://www.nrcaf.ernet.in/ aicrpaf/pdf/angrau.pdf
Wage	unskilled	90	Rs / day	http://www.nrcaf.ernet.in/ aicrpaf/pdf/angrau.pdf