MODELING FOR DEVELOPING A SUSTAINABLE CITY WITH MINIMIZED EMBODIED ENERGY

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Abstract

In the modern era, environmental sustainability is a topic of concern. A key issue of worry in the current situation is global warming, which is influenced by the growing level of carbon emissions. In addition to the direct emissions from industry and automobiles, construction also contributes to excessive carbon emissions. Low embodied energy of a material during construction of the building implies environmentally sound. The quantity of energy utilized during the production of the material is known as the embodied energy. The model is built as a multi-objective constrained optimization problem. The findings help to determine how much of each type of material should be utilized to create a city that is as sustainable as possible. This essay offers a comprehensive plan for developing an energy-efficient, environmentally friendly metropolis. The total amount of energy used throughout each stage of a product's lifecycle, which includes extraction, production, transportation, and disposal, is known as embodied energy. As cities continue to expand and consume significant amounts of resources, it is imperative that urban landscapes be planned and constructed in a way that minimizes their negative environmental effects and promotes long-term sustainability. The major objective of the study is to identify key strategies and considerations for urban planning while minimizing embodied energy. These tactics encompass a variety of subjects, including material selection, building methods, infrastructure for transportation, and waste management. By utilizing these factors to their full potential, cities may significantly cut down on their energy use and carbon footprint.

Keywords: Sustainability, Embodied Energy, Materials Cost, Material selection.

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1.Introduction

Recently, materials with a high energy requirement have been utilized in construction projects. Conventional building systems, while constructed with the best ventilation possible, do not fully utilize natural ventilation, which places a heavy burden on the power grid and causes energy depletion. The construction industry can lessen its contribution to global emissions by looking into alternative sustainable building materials, or materials produced with less energy. The goal of the study is to find methods and strategies for enhancing the building's embodied and operational energy. To the greatest extent possible, a material must be used in its natural state or processed with the least amount of technological intervention in order to minimize the embodied energy. Without having a negative effect on the environment, the materials and technology chosen for building construction should satisfy both user wants and societal development needs. Lighting and space conditioning (thermal comfort) account for the majority of operational energy usage in buildings. Additionally, it depends on the local climate and the occupants' needs for comfort. The community's health is greatly endangered by the materials made using components that generate pollutants. Concrete can be replaced with wood to reduce carbon emissions by 68% and 43%, respectively. Calculation uncertainty for embedded energy and carbon heavily depend on geographic locations. The goal for operating energy optimization is coming close to zero, and research into reducing embedded energy is doing well. It has been shown that a small increase in cost will reduce embodied energy. Different LCI methodologies generate variances in Embodied Energy factors, or the amount of EE that can save one unit of Operation Energy, in several research that examine the relationship between Embodied Energy and Operation Energy. Studies comparing the performance of natural building systems to conventional systems are urgently needed as awareness of the benefits of environmentally friendly buildings on human health and the environment has grown recently. Therefore, by contrasting traditional and regenerative design, this study seeks to reduce the embodied energy and operational energy of the design. The school building construction typology was chosen because it involves more significant functional and energy aspects. When making decisions to build a sustainable city with the least amount of embodied energy, urban planners, architects, and policymakers can find a lot of support from modelling approaches. The energy efficiency of various urban components can be examined and improved, the environmental implications of design choices can be predicted, and the sustainability of the city can be evaluated over the long-term using a variety of modelling tools. Modelling for life cycle assessment (LCA): LCA is a widely accepted methodology for determining how products, materials, and activities affect the environment over the course of their entire life cycle. Calculating the embodied energy of different construction materials, transit systems, and waste disposal strategies is possible when LCA is applied to urban design. Using LCA modelling, the most energy-efficient options can be identified and suggested.

1.1 Embodied Energy

The energy needed to make, move, and install building materials and components is referred to as embodied energy. It has a considerable impact on a building's carbon footprint. The construction industry may lessen its negative effects on the environment and develop more sustainable structures by employing materials with low embodied energy, such as locally sourced and renewable materials. This comprises of the energy expended on raw material extraction and processing, building material production, transportation and distribution, and assembly and construction. When estimating embodied energy, the cradle-to-grave method also considers the energy needed for rehabilitating and maintaining infrastructures throughout their useful lives as well as for demolition and waste disposal at the end of those lives. Embodied energies for frequently used building materials, measured in MJ/kg. By comparing the energy needed to make different construction materials, the embodied energy concept can be used to assess their sustainability. The kind of construction materials deployed, production effectiveness, transportation distance, material durability, and construction techniques used all have a big impact on how much energy is really embodied in a project. Durable materials have a longer lifespan and require less energy overall during their lives. The embodied energy of recycled materials is likewise substantially lower than that of their virgin counterparts because there is no longer any energy needed for the extraction and processing of raw materials. In order to produce PP fibers from virgin plastics, for example, crude oil, coal, or natural gas must be extracted, transported, and processed in refineries before being polymerized and turned into plastic pellets and granules. However, the production of PP granules from recycled plastic feedstock removes the extraction and processing of fossil fuel and significantly lowers the embodied energy of recycled plastic goods. With a 70% recycled component, recycled PP has an embodied energy of about 25 MJ/kg less than that of virgin PP.

1.2 Different Types of Bricks

Sun-dried Bricks: These are un-burnt bricks made of clay. They are molded and left under the sun to dry.

Burnt Clay Bricks: Burnt clay bricks are made of clay and put into the kiln for burning. They are used for building walls, foundations, and columns, among others. There are four different types of burnt clay bricks:

- First class: Quality with excellent edges
- Second class: Ground molded and a bit irregular in shape
- Third class: Rough-edged and ground molded, used for temporary construction
- Fourth class: Over-burnt and highly irregular, dark in color with no water resistance feature

Fly Ash Bricks: It is also called Self-cementing brick; these bricks contain Class F or Class C fly ash as a part of the formula. Fly ash is collected from the furnaces of industries where coal is burned. This ash has passed through 1, 000 degrees Celsius heat and contains calcium oxide.

Concrete Bricks: These bricks are made using solid concrete. The concrete is prepared using sand, coarse aggregates, water, and cement. The shape and size can be tailored according to specific requirements.

Engineering Bricks: This type of brick offers high compressive strength. They are used for construction where low porosity, frost resistance, acid resistance, and strength are mandatory. Such bricks are generally applied for creating the basements of buildings.

Calcium Silicate Bricks:
Also called sand lime bricks, they are made by mixing fly ash, lime, and sand. It is used for masonry and ornamental works in different construction projects.

Eco Bricks: Prothema hollow bricks are suitable walling solutions. They offer significant thermal insulation and make walls stronger. The perforations in them can be either horizontal or vertical.

Cost of Different Types of Bricks in India

Here is a list of the cost of brick types based on the average price range:

Types of Bricks	Burnt clay bricks	Fly ash bricks	Concrete bricks	Engineering bricks	Calcium silicate bricks	Eco bricks
Cost (Rupees/ piece)	5 to 8	4 to 6	5 to 6	10 or above	100 average	4 to 5

1.3 Different Types of Cements

Cement is a crucial building material used in construction projects to bind materials together and form a strong, durable structure. There are several types of cement available, each with unique properties and applications.

(a) Ordinary Portland Cement 33 Grade

It's typically used to the level of M20 grade concrete for common civil construction tasks like masonry, flooring, and plastering. Less cracking is guaranteed by the low compressive strength and low heat hydration of this type of cement. However, this kind of cement is not as common in the marketplace. It has the Indian Standard code 269 assigned to it.

(b) Ordinary Portland Cement 43 Grade

They are utilized for ordinary civil uses like plastering and flooring up to M 30 concrete grades, much to OPC 33-grade cement. The minimum compression strengths for this kind of cement are 43 Mega-Pascal after 28 days. Despite being gradually displaced by blended form cement, this type of cement is still widely accessible on the market because of its extensive use in the construction sector. The Indian Standard code for Ordinary Portland Cement is 8112.

(c) Ordinary Portland Cement 53 Grade

For general uses including the construction of bridges, roads, multi-story building projects, etc., this type of cement is used with concrete that is stronger than M30. After 28 days of curing, they reach the required compression strength of 53 Mega-Pascal. They are also frequently employed in reinforced cement concrete, a complicated material in which reinforcement is added to concrete that has relatively low tensile strength and ductility in order to increase that strength and ductility. Application is shown in immediate plugging mortars and cement grouts, which both call for higher strengths. It is assigned the 12269 Indian Standard code.

(d) Portland Slag Cement (PSC)

The Portland Slag type of cement is chosen over regular Portland Cements because it does not shatter when exposed to harsh environments like wastewater treatment or maritime applications. Due to its tremendous strength, it works best for long-lasting services like highways or bridges as well as tall constructions. Its characteristics work wonderfully with Portland cement to increase strength, which reduces permeability and improves resistance to different chemical reactions like chlorine and sulphate attacks or even straightforward corrosion. Contrary to other cement varieties, this is only offered in particular markets. The Indian Standard code for this cement is 455.

(e) Colored Cement (White)

Produced using iron oxide and manganese oxide as starting ingredients, a material that is frequently utilized to improve the aesthetic of buildings on the inside and outside. These are much more expensive but they have their advantages to justify the price. Examples include terrazzo tiles, ornamental concrete items like idols and non-structural floors, and special effects. As its name implies, it is white in color, and its chemical make-up and physical characteristics are also in line with those of Ordinary Portland cement. The Indian Standard code for colored cement is 8042.

(f) Portland Pozzolana Cement (PPC)

Portland Pozzolana is renowned for its fineness, high level of impermeability, and ability to resist corrosion, which makes the concrete dense and increases the longevity of the construction. This type of cement is used in place of regular Portland cement in unfavorable soil conditions because of its high impermeable quality and long-term strength of more than 90 days. As a result, it is used to build hydraulic structures like dams and retaining walls, marine structures like bridge footings in harsh conditions, and even simple masonry work like plastering. Portland Pozzolana Cement is conveniently offered in marketplaces. The Indian Standard code for this cement is 1489 P-2.

(g) Hydrophobic Portland Cement

The Hydrophobic Portland cement is more expensive than the Ordinary Portland Cement and less widely available due to the market's glut of different types of cement, but it is best used in harsh cold weather conditions because it is made with the specifications needed in areas with heavy rainfall to extend its life. This cement is used in the construction of spillways, dams, and other underwater constructions because it has a chemical coating applied during manufacturing that makes it effective at repelling water, as the name implies, and prevents it from being damaged by high humidity. The Indian Standard code for this cement is 8043.

(h) Hanger /Shoulder Bricks

Ramani Ceramics produces high quality hangers & shoulder bricks. Our highly qualified technicians take utmost care in maintaining the quality of bricks. There are three qualities of Hanger & Shoulder Bricks according to their specifications.

(i) Hanger & Shoulder Bricks 40% Alumina

It contains a minimum of 40% Alumina & maximum 2.2% Ferric. The PCE O. C. content is 32. Its minimum bulk density is 2.1 gm/cc and its apparent porosity is maximum 23%. It has a cold crushing strength is 250 Kg/cm2. The refractoriness under load is minimum 1400 (Ta °C). These types of bricks generally serve the purpose of high heat duty bricks.

Hanger & Shoulder Bricks 50% Alumina

It contains a minimum of 50% Alumina & maximum 2.5% Ferric. The PCE O. C. content is 35. Its minimum bulk density is 2.3 gm/cc and its apparent porosity is maximum 22%. It has a cold crushing strength is 350 Kg/cm2. The refractoriness under load is minimum 1430 (Ta °C). These bricks are used for re-heating furnace.

Hanger & Shoulder Bricks 70% Alumina: It contains a minimum of 70% Alumina & maximum 3% Ferric. The PCE O. C. content is 36. Its minimum bulk density is 2.65 gm/cc, and its apparent porosity is maximum 23%. It has a cold crushing strength is 400 Kg/cm2. The refractoriness under load is minimum 1470 (Ta °C). These bricks are used for re-heating furnace.

Figure 1 : Types of bricks

2. Literature Review

The previous studies showed that the amount of primary energy consumed by buildings is close to half of the total, while the recent study shows embedded energy being used in residential buildings may represent up to 40% of the energy used throughout the life of residential constructions. Studies have until now primarily concentrated on energy saving in building operation. Buildings embodied and demolition energy have different intensities and a model has been created to calculate these intensities. This study uses a life cycle assessment (LCA) methodology to evaluate the embodied energy of a typical residential construction in India. According to the findings, the residential building has an embedded energy of roughly 5900 GJ with the manufacturing stage using the most energy (50.3%). 38.8% of the total embedded energy is used with the other stages being transportation, building and end-of-life accounting for 6.7%, 3.3%, and 1%, respectively of the total. Concrete, steel, and aluminum are the materials with the highest energy usage. Meeting the global challenges of urbanization, resource depletion and climate change requires sustainable cities. Keeping embodied energy of the literature on low carbon and low embodied energy materials in buildings is reviewed in this study. Embodied energy is described and contrasted with operating energy. Embodied energy is defined and contrasted with operating energy used by buildings as well as its expanding significance as a result of the adoption of the Energy Building Performance Directive (EBPD). Embodied energy and embodied carbon dioxide, often known as the CO2 footprint, are related. They include cement and concrete, wood, bricks, rammed earth, and sandstone, among other materials that have been identified in the literature as low carbon materials. The review highlights the research efforts used to create novel materials with minimal waste that were found in the literature. Structures and infrastructure to a minimum is essential for sustainable cities. Embodied energy is the energy used throughout the whole life cycle of a structure or piece of infrastructure, encompassing the stages of raw material extraction, production, transportation, construction, use, and end-of-life. To reduce greenhouse gas emissions and advance sustainable development, it is essential to minimize embodied energy. The manufacturing and delivery of different building materials consume a substantial amount of energy. When greenhouse gas emissions are controlled and material costs are brought down, energy conservation becomes crucial. The embodied energy in buildings is the primary topic of the article, with an emphasis on India. This study examines the methods and recommended actions for creating a sustainable city with the least amount of embodied energy. The significance of the embodied energy idea for sustainable cities is first covered in this review.

A common methodology for assessing the environmental effect of products, materials, and processes over the course of their full life cycle is life cycle assessment (LCA). By using LCA to analyses urban growth, it is possible to calculate the embodied energy of different building materials, transportation infrastructure, and waste disposal methods. The most energy-efficient options can be found with the aid of LCA modelling, which can also direct decision-making towards low-impact options. Building energy modelling: A large amount of the energy used in cities is consumed by buildings. Energy modelling programmers, such Energy Plus or Design Builder, may simulate a building's energy performance and evaluate the embodied energy of various design options. Building designs can be optimized by architects and engineers to minimize costs by modelling variables like insulation, lass, and HVAC systems. The built environment is responsible for at least 40% of total greenhouse gas emissions, mostly due to the use of energy from fossil fuels. To combat this, developers have created energy-efficient buildings, such as "green" or "net-zero energy" developments. However, while these buildings may reduce operational energy use, studies have shown that they often have trade-offs in terms of embodied energy in construction materials and transportation energy associated with building users. Reducing energy use and carbon emissions in buildings is essential for achieving global carbon neutrality since the construction industry has emerged as a major source of carbon emissions. In order to find ways to decrease CO2 emissions from a macro perspective, a study was done to assess the annual total energy and carbon embodied in the 10 most popular building materials in China. The results showed that over 70% of the embodied energy and carbon in all building components came from cement, steel, and brick. Although there were large variations in embodied energy and carbon between building materials in different regions, the differences in embodied energy and carbon between steel-concrete and brick-concrete structures were not very noticeable. In comparison to other regions, the eastern and south-eastern parts of China consumed more building materials and included a disproportionate amount of energy and carbon. The report suggests a number of methods for China's building industry to cut energy use and carbon emissions, which might lessen the sector's carbon footprint and support efforts to achieve global carbon neutrality.

3. Design, framework, and modelling

The model is framed to minimize two objectives such as the total embodied energy and the total material and construction cost. The plan is to make a sustainable city design in which several locations are considered. The example of the design of Lovely Professional University (LPU), India is provided in this study.

The LPU campus is assumed as the main location and this is divided into many sub-locations such as School of Computer Science and Engineering (SCE), School of Mechanical, Unpolish Stadium, Indoor sports complex, Boy's Hostel, and Staff Quarters (Figure 2).

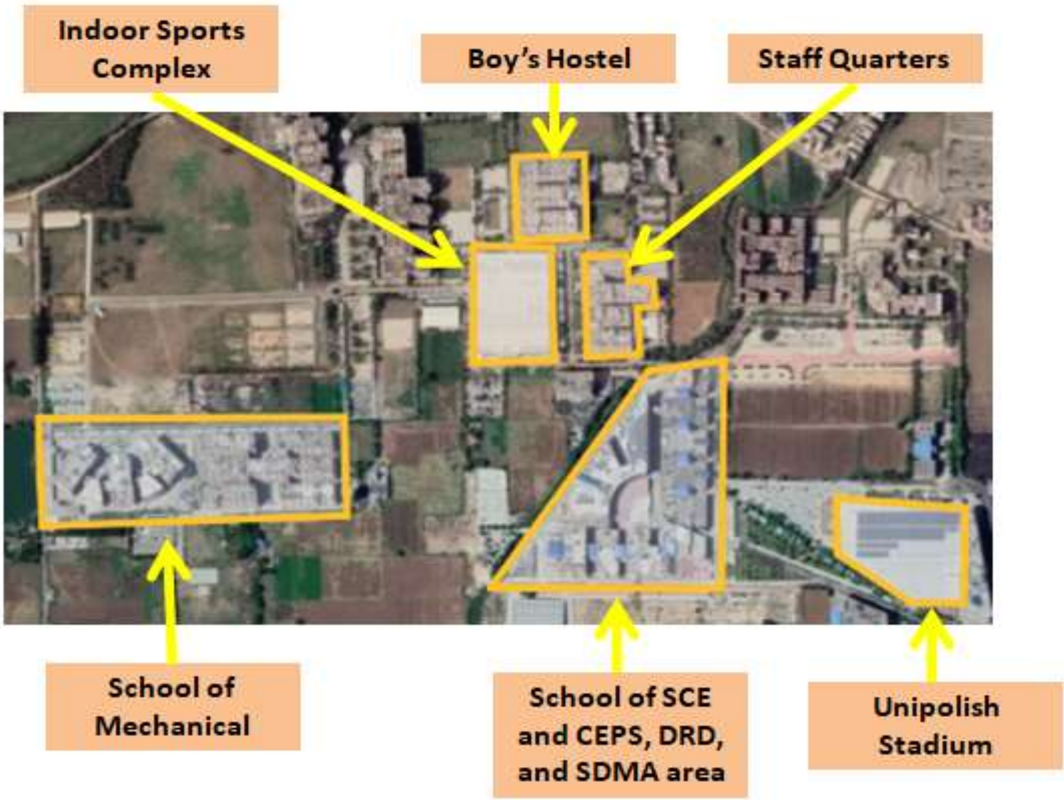

FIGURE 2 : THE SUB-LOCATION IN LPU CAMPUS AREA

TABLE 1 : THE APPROXIMATE AREA AND PERIMETERS OF THE PREFERRED LOCATION

Location	Name	Area	Perimeter
1	School of SCE and CEPS, DRD, and SDMA area	49,186.47 m²	972.59 m
2	School of Mechanical	46,710.83 m²	979.96 m
3	Unipolish Stadium	15,383.04 m²	498.06 m
4	Indoor Sports Complex	11,342.63 m²	433.58 m
5	Boy's Hostel	7,121.62 m²	339.89 m
6	Staff Quarters	6,834.93 m²	394.60 m

It is observed from Table 1, that the maximum area 49,186.47 m² covers the School of SCE and CEPS, DRD, and SDMA area. Lowest area is covered by the Staff Quarters area which is 6,834.93 m². We consider clay bricks, steel rods, cement, and fly ash bricks. Table 2 represents the embodied energy and cost per kg for each material.

TABLE 2 : EMBODIED ENERGY AND COST PER KG OF MATERIAL

Material	Embodied energy (MJ per kg)	Cost of material (Rs. per kg)
Clay bricks	1.64	2
Steel rods	32.0	72
Cement	6.70	110
Fly ash blocks	0.56	3

We consider x_i^k as the amount (kg) of i^{th} material of location k which are supposed to be the decision variable.

Total embodied energy (TE_m) for materials

$$TE_m = \sum_i E_i x_i^1 + \sum_i E_i x_i^2 + \cdots + \sum_i E_i x_i^n$$

Where, n is the number of locations, x_i^k denote the amount of i^{th} material for location k, and $E_i$denotes the embodied energy of type i^{th} material.

Total Cost of materials and construction (TC_e)

$$TC_e = \sum_i \tilde{c}_i^1 x_i^1 + \sum_i \tilde{c}_i^2 x_i^2 + \ldots\ldots\ldots \sum_i \tilde{c}_i^n x_i^n,$$

Where C_i^k denotes the cost of i^{th} material of location k (unit cost).

Set of constraints

Suppose maximum capacity of the i^{th} material needed for location j is B_{max}^j and let the maximum amount of embodied energy should not exceed $E^j{}_{max}$ for location j.

$$\sum_i x_i^j \leq B^j{}_{max}$$
$$\sum_i E_i\, x_i^j \leq E^j{}_{max}$$

Thus, the problem is designed to minimize the total material cost and the total embodied energy under the constraint set (3).

$$Minimize\ TE_m = \sum_j \sum_i E_i x_i^j \qquad (1)$$
$$Minimize\ TC_e = \sum_j \sum_i c_i x_i^j \qquad (2)$$

Subject to the constraint

$$\sum_i x_i^j \leq B^j{}_{max}$$
$$\sum_i E_i\, x_i^j \leq E^j{}_{max}$$

4. Solution methodology

The problem statement is a multi-objective minimization problem. One of the efficient ways to solve the basic problem statement is the weighted sum method. The basic multi-objective minimization problem is as follows.

$$Minimize\ f_1(x), f_2(x), \ldots, f_n\ (x)$$
$$g_j(x) \leq 0; \text{for all } j$$
$$h_k(x) = 0; \text{for all } k$$
$$x \geq 0$$

The weighted sum method is designated to combine all objective functions by multiplying a weight $w_i$so that

$$Minimize \sum_{i=1}^{n} w_i f_i$$
$$g_j(x) \leq 0; \text{for all } j$$
$$h_k(x) = 0; \text{for all } k$$
$$\sum_{i=1}^{n} w_i = 1,$$
$$x \geq 0$$

The different values of w_i provides pareto solutions.

5. Conclusion

A consent on embodied energy characterization and system boundary selection rules could be a credible research work, as it could help make embodied energy calculation guidelines. Besides, assessment of restriction impacts identified in this. Embodied energy, which includes all indirect and direct energy consumption, can offer more complete results of energy usage. It can help with understanding ways to increase the economic system's energy sustainability and efficiency and then offer suggestions and guidance for policymaking to promote energy security. Indeed, there are still a lot of obstacles to overcome before we can fully understand the value of embodied energy in the research and application of energy security issues due to the limits of the data foundation, research foundation, and methodology. Therefore, it will still be worthwhile to develop relevant themes in the future. As a result, modelling to develop a sustainable city with the least amount of embodied energy requires a thorough understanding of the relationships between urban components, the incorporation of various modelling methodologies, and the consideration of social, economic, and environmental factors. It gives decision-makers the power to choose wisely, optimize urban plans, and create sustainable communities that consume less energy, have fewer adverse effects on the environment, and enhance the quality of life for residents. We can pave the path for a period when cities are not only energy-efficient but also resilient, sustainable, and attuned to their environment by utilizing modelling approaches and technologies.

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