Lee, B., Trcka, M. and Hensen, J. L. M., 2011.
Embodied energy of building materials and green building rating systems - a case study for industrial halls.
Sustainable Cities and Societies, 1(2), pp. 67-71.

EMBODIED ENERGY OF BUILDING MATERIALS AND GREEN BUILDING RATING SYSTEMS - A CASE STUDY FOR INDUSTRIAL HALLS

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Abstract: Green Building Rating (GBR) systems are developed to provide independent assessment standards that evaluate in a few categories about the performance and sustainability of buildings. However, same category might weight differently in each of the GBR systems. A particular system might favor certain strategies over others due to difference in weighting. This is particularly the case for industrial halls since current GBR systems are catered more for commercial buildings than for industrial halls, which pose a significantly different geometry. This paper explores the impact of different building materials (concrete vs steel) on the embodied energy of the building structure, and compares that to the GBR score earned under the material category for the same structure. Through a sensitivity analysis in the calculation of embodied energy, the major source of uncertainty is identified and its effect on GBR score is discussed. This paper forms part of a project that also studies the operation energy and the demolition energy of building, which together with the embodied energy constitute the total life-cycle-energy demand.

Keywords: industrial hall, green building rating, embodied energy, life-cycle energy analysis, sensitivity analysis

1. Introduction

Modern buildings have to achieve certain performance requirements, at least to satisfy those of building codes, to provide a safe, healthy, and comfortable environment. However, these conditioned environments demand resources in energy and materials, which are both limited in supply, to build and operate. Within this context of limited resources, the goal is to construct buildings that could provide better performance and yet demand fewer resources; in other words, to do it in a sustainable fashion. Sustainable strategies are best incorporated into the early stages of the design process.

Green Building Rating (GBR) systems (a.k.a. certification systems) facilitate the sustainable design processes by providing independent assessment tools, in which strategies used to improve sustainability of buildings can be evaluated according to common sets of rules that cover categories from energy efficiency to water resource. Because of the diverse scopes and objectives of GBR systems, and the ways GBR scores are calculated, a highly rated building might not perform well when compared to actual performance data. For example, it was found that at least 28% of LEED (Leadership in Energy and Environmental Design) certified buildings consume more energy than conventional buildings [1]. This finding is understandable in certain cases in spite of its high significance; that is because energy efficiency of building operation just represents a single aspect of sustainability. By the same token, an energy efficient building with poor building material choices may not be considered sustainable.

A possible alternative to gauge sustainability is to represent any of these categories in a common unit; for example, in the unit of energy, or more specifically, the total life-cycle energy demand. It includes:

- the embodied energy involved in the acquisition, processing, manufacturing, and transportation of building materials during the construction phase;
- the operation energy of the building; and
- the demolition energy in the destruction, removal, and recycling of building materials.

With the advent of Building Information Modeling (BIM), building materials data from the construction phase till the demolition phase could be made available, and energy involved in each of these phases could be estimated [2]. The total demand for the whole life-cycle can serve well as a yardstick for assessing sustainability.

This paper presents some preliminary results of an on-going project “Sustainable Energy Producing Steel Frame Industrial Halls”. The project takes on the whole life-cycle approach towards total life-cycle energy demand of the building, in particular, a steel frame industrial hall. The goal of that project is to develop computational design and assessment support tools that could facilitate the design of energy producing industrial halls, in which the halls are fitted with sustainable energy technologies that satisfy if not to exceed the energy demand of the halls. Therefore, a thorough investigation of total life-cycle energy demand is the natural first step. The investigation will be performed in parts, in terms of the embodied energy, the operation energy, and the demolition energy. This paper presents the results of the first part - the total embodied energy in the building structure due to material choice. To illustrate the idea, a case study of a typical industrial hall, which is constructed with two different building materials - concrete and steel, is presented. The embodied energy results will be compared to the GBR scores earned under the material category.

2. Assessment of sustainability of building materials

The sustainability of a building material could be commonly measured by, the reclamation rate and the recyclability of the retired building material, and the recycling content of the new building material.

Buildings come to their end-of-life usually not because of any structural issue, but rather the original purposes of the buildings shift; and existing buildings no longer support their new roles and functions. The possibility of remodeling depends largely on how flexible it is for the original building to adapt to its new roles. Concrete structures can only be modified to a certain extent at a cost that might be more expensive than building new structures [3]. By contrast, steel structures, which in many cases are bolted together, facilitate deconstruction and reuse. Readapting existing building for other purposes, or reusing existing building materials for the construction of a new building not only saves new materials from being used, but also cuts the associated environmental impacts of producing and transporting those materials.

When the building is demolished, steel is commonly being recycled (or reuse) in practice. In the UK, 86% of structural steel was recycled with another 13% reused [4], and in the U.S., 97.5% of structural steel was recycled [5]. The recycled steel is being made into other steel products. In the case of concrete, the most common recycling option in urban areas is to crush it into coarse aggregate mainly to serve as road base or fill [6]. The recycle potential of concrete is therefore limited by the demand of the recycled end-product (coarse aggregate) and the proximity to possible sites of application (where road works are within economical travelling distance of the demolition site).

The proportion of recycled content of the new materials is also an indicator to sustainability. Since the demand for steel products is greater than the supply of scrap steel, it is inevitable to have a certain percentage of virgin steel in any steel products. As for concrete, the bulk is just natural materials like sand or crushed rock. The binding agent, cement, can be replaced by up to a certain percentage with industrial waste products like fly ash, blast-furnace slag, and silica fume [6], which are added as additives. The replacement not only improves the quality of concrete but also eliminates the environmental impacts of having to dispose the otherwise dumped wasted products.

2.1 Green Building Rating (GBR) systems applied to building materials

Many GBR systems are available today and these systems differ greatly in their purposes and scopes. In general, they all concern about reusability and recyclability, but the amount of credits available and the criteria to achieve the credits are vastly different. Due to the limited length of this paper, only the LEED system is discussed.

2.2 LEED

Under the LEED 2009 Rating System (part of version 3 certification program) [7], 14 points can be awarded under the "Materials and Resources" (hereafter referred as "material") category and worth close to 13% of all available points. LEED's emphasis is on reuse and recycling. Table 1 lists the sub-categories and points under this category.

Points are awarded if more than 55% of the exterior structure or more than 50% of the interior non-structural elements are retained for Credit 1. With Credit 2, points are awarded for demolished building materials (from the retired building) being diverted from the disposal to being reused for the assessed building or being recycled. Aside from the environmental benefits, the possibility of recycling and reusing also provides economic incentives to the building owners by avoiding dumping costs, and profiting from the sale of the scraps. For example, if concrete from the retired building can be recycled as fill or road base, this credit can be achieved. By the same token, LEED also awards points to buildings using reclaimed materials under Credit 3, in which the materials can be transferred from another site, or acquired from suppliers; bolted steel structure makes this credit easily attainable.

In the case where building materials must be purchased new, the recycled content of structural steel can reach a high percentage that guarantees the award of Credit 4. Recycled materials, such as fly ash, blast-furnace slag, silica fume, in precast concrete also help to attain this credit.

Credit 5 is awarded for use of local / regional materials that is within 800 km of the project site. The fabrication shop, which does cutting, drilling, and welding, for structural steel is considered to be the location of manufacturing; and as a result, this credit is likely attainable for any site location, particularly for those in Europe.

2.3 General issues with GBR systems

GBR systems, under most categories, are prescriptive-based (for example, the material category of LEED), in which credits are given if certain prescribed values are achieved in the design; and under a few categories, are performance-based, in which the performance of the building for such categories have to be proved to offer certain improvement over a benchmark. Due to this mix of prescriptive and performance based scoring methods, together with the difference in weighting assigned to different categories and the rule-of-thumb values used in the rating of each category; the resulting GBR scores might be highly distorted.

2.4 Embodied energy - another view of sustainability of building materials

In fact, the embodied energy of the building materials can serve well as an alternative metric to reflect the sustainability of the materials. The energy involved in the reclamation, the recycling, and the manufacturing processes of building materials as described in earlier section can all be estimated and accountable for with BIM, even at a very early stage during the design phase with available databases.

3. The case study

In this section, the calculation of embodied energy and the influence of uncertainty in the calculation will be explored. A case study building that represents a rectangular shape industrial hall of 80m width x 170m depth x 6m height, is being studied. The building is built with two exemplary construction methods:

- steel cladding on steel frame with steel deck on steel joist, and
- reinforced concrete wall with concrete deck on steel joist.

3.1 Inventory of the building materials for the case study

The steel frame example consists of exterior walls of IPE 400 steel stud with steel profiled cladding of 0.7 mm, and an open web joist roof of IPE 200 and IPE 100 beams with steel structural deck of 1 mm. A summary of the total amount of steel used in the wall and roof is presented in Table 2.

The concrete example consists of tilt-up reinforced concrete walls of 200 mm thickness, with a concrete slab of 75 mm supported by open web steel joist. Because of the weight of the concrete slab, the steel joist has to be spaced at tighter distance. The concrete slab is commonly placed on steel deck (in place of rebar) of nominal thickness that weighs roughly the same as the replaced rebar.

Because of the weight of the concrete slab and the long unsupported span (manufacturing processes usually demand spaces with fewer columns), the open web structure that has to be placed to support the concrete slab is more massive than that of the steel roof structure. Table 2 indicates that the amount of steel placed in the roof of the concrete example is in fact more than that of the steel example. In practice, concrete roof is not a common option for industrial hall not just because of its weight, but also because it serves no additional purpose. The roof for industrial hall is usually of either steel or built-up construction. To illustrate the idea, a third example is studied, it is a hybrid structure with wall of the concrete example and roof of the steel example. A breakdown of mass according to material and structural component is presented in Table 2.

3.2 Sensitivity analysis in the calculation of embodied energy

In the calculation of embodied energy of the building structure, there will always be uncertainty in:

- the amount of materials used,
- the embodied energy of the materials, and
- the source and content of the materials.

It is thus important to estimate the range of uncertainty of the input parameters such that the resulting uncertainty in the embodied energy of the building structure can be predicted and the most influential input parameters can be identified.

3.3 Uncertainty in the amount of materials

Based on the case study building, it is estimated that the industrial hall is composed of 507 tonne of steel for the steel structure, and of 3,888 tonne of concrete with 475 tonne of steel for the concrete structure. The estimate might not represent any industrial hall for a particular industry. Due to the diversity of industries (that impose different structural requirements) and variations in construction techniques, the amount of materials used in the building structure may deviated from what it is estimated here. Because of this hypothetical nature, the uncertainty range should therefore be treated as uniformly distributed, and is assumed to be ±20%.

3.4 Uncertainty in the embodied energy of the materials

The embodied energy of the building materials (concrete and steel) is based on the two widely referenced embodied energy coefficient databases [8, 9]. The average embodied energy of high strength concrete is 1.5

MJ/kg, and those of virgin steel and recycled steel are 33.7 MJ/kg and 9.8 MJ/kg, respectively. The average values are deviated from their original values (Table 3) by 3 to 7%.

There are multiple steps involved in the production and delivery of building material to the building site; the proximity of the manufacturing facility to the building site, and the whole logistic of the manufacturing process play a significant role in determining the embodied energy of a building material. The Athena's database [10] for building assemblies provides data for a number of U.S. and Canadian cities. The embodied energy of building assemblies varies among cities, and falls within a range from the national average of ±5% for U.S. cities, and ±10% for Canadian cities. This ±10% range represents the largest variation presented in the studied literature; therefore, the embodied energy values are assumed to have a confidence interval of ±10% with a confidence level of 90%, normally distributed (since the assumed embodied energy values are drawn from databases, and are assumed to be typical).

3.5 Uncertainty regarding the source and content of the materials

There are basically two types of steel production facilities, namely the basic oxygen furnace (BOF) and the electric arc furnace (EAF), with an average recycled content rate of 32.7% and 93.3% respectively [11]. Since the production of EAF is 50% more than that of BOF, the embodied energy of recycled steel can be modelled as the embodied energy of virgin steel (33.7 MJ/kg) being reduced by either 23.3% or 66.4%, depending on the production facilities, in which the reduction of 66.4% is 50% more likely than that of 23.3%.

It is estimated that for every 1% replacement of cement with fly ash, the embodied energy of concrete is reduced by 0.7% [6]. Based on the findings in the literature, a 10% replacement of cement with fly ash is a common practice to improve the overall property of concrete, and a 50% replacement is seldom applied. The replacement can be translated into a triangular distribution of a very likely case of 7% to an unlikely case of 35% reduction in the embodied energy of concrete.

The embodied energy of steel and concrete assumed in this paper and the corresponding possibilities in reduction are summarized in Table 4.

4. Results

The results of the case study with three exemplary new built structures are presented here.

4.1 Monte Carlo simulation of embodied energy in the building structure

The commercial quantitative risk analysis package @RISK [12] is deployed to perform a Monte Carlo simulation (with 10,000 iterations) that predicts the possible embodied energy of the three exemplary building structures with randomly generated values for the input parameters according to the selected probability distribution as described in the previous sections. The results are presented in Figure 1.

Table 5 summarizes the statistics of the simulation. The embodied energy of the whole concrete structure is significantly more than that of the steel or the hybrid structure.

Some input parameters have a greater impact than the others on the resulting embodied energy of the building structure. The correlation coefficients (Spearman Rank) of the top three inferential input parameters are presented as tornado chart in Figure 2.

Because of the vast amount of steel presented in any of the three structures, the uncertainty in the recycled content of steel causes the most impact on the resulting embodied energy. The comparatively larger roof surface (than the wall surface) also makes the input parameter - mass of roof in steel, the second most influential one.

4.2 GBR scores of the building structure under the material category

GBR systems award credits or points in a discrete manner, which in many cases lead to a "all or none" situation. To illustrate the point, LEED is presented here as an example. If the construction is a new built on ground with no existing structure, the credits available for LEED are Credit 4 (2) and Credit 5 (2). LEED requires a recycled content of 10% by total cost to achieve 1 point and 20% for an extra point in Credit 4. Since the recycled content of steel is assumed to be at least 32.7%. A high recycled content of steel guarantees the award of 2 points for both the steel and the hybrid structures.

Any jobsites in the urban or suburb areas that have ready access to regional materials (within a distance of 800 km) could easily earn 2 points for Credit 5. Out of the 13 LEED points under the material category, Table 6 lists the possible points achievable for a new built.

From Table 6, it could be observed that regardless of the recycle content of steel or the construction method, the points achievable under the material category are similar under the LEED system.

5. Discussion

Even though the LEED points earned under the material category show little or no variation among structures of different constructions. The embodied energy of the concrete structure is double that of the hybrid structure. There is a discrepancy between the results of the calculation of LEED points and that of embodied energy. There are two reasons for the discrepancy; one being the issue of applicability of GBR systems to industrial halls, and the other being the way points are awarded.

First of all, Credit 4 of the material category of LEED requires a mere 10% recycled content by cost to earn 1 point, and 20% to earn 2 points. The prescriptive values are suitable for commercial buildings, in which the construction is complex and is fitted with high value assemblies. 10% or 20% recycled content by cost already reflects the effort made in choosing the more sustainable materials. By contrast, the prescribed percentages are readily achievable for industrial halls, which are constructed with simple steel or concrete assemblies that are high in recycled content. The prescribed percentage simply falls outside the recycle content ranges of the building materials for the industrial halls. In other words, improvement in material choice for the industrial halls simply cannot be reflected under the LEED system.

Secondly, points under the LEED system are awarded in limited number of levels - usually two; 10% or 20% of recycle content, for example. The limited number of levels does not reflect the possible range of uncertainty for embodied energy - an indicator of sustainability. As presented in Table 5, the range of predicted embodied energy of the concrete structure is from 8.0 to 20.6 thousand GJ; the range of uncertainty as a percentage ratio between the embodied energy range of the concrete structure to that of the steel structure is from 36% to 320%. In order to adequately reflect the impact on sustainability due to the vast possibilities in construction methods, points for the LEED system should be awarded in finer steps.

6. Conclusion

Through a simple case study with three exemplary new built structures, this paper demonstrates the potential deficiency of GBR systems, particularly for industrial halls, which might lead to misleading scores that do not accurately represent the actual performance of the structures. The case study could be expanded to include more complex scenarios; for example, the incursion of the demolition or retention of an existing structure so as to reveal the impact on:

- embodied energy (of the assessed structure), and
- demolition energy (of the existing structure that counts towards credits of the assessed structure)

and to explore the corresponding GBR points that could be earned.

The impact of building materials does not limit to the embodied energy and the demolition energy but also to the operation energy of the building. This will be studied in the future. The whole life-cycle energy demand shall provide better representation for sustainability of building structures.

Acknowlegement

This research was carried out under the project number M81.1.08318 in the framework of the Research Program of the Materials innovation institute M2i (www.m2i.nl).

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Figure 1. Probability distribution of total embodied energy of the three exemplary building structures.

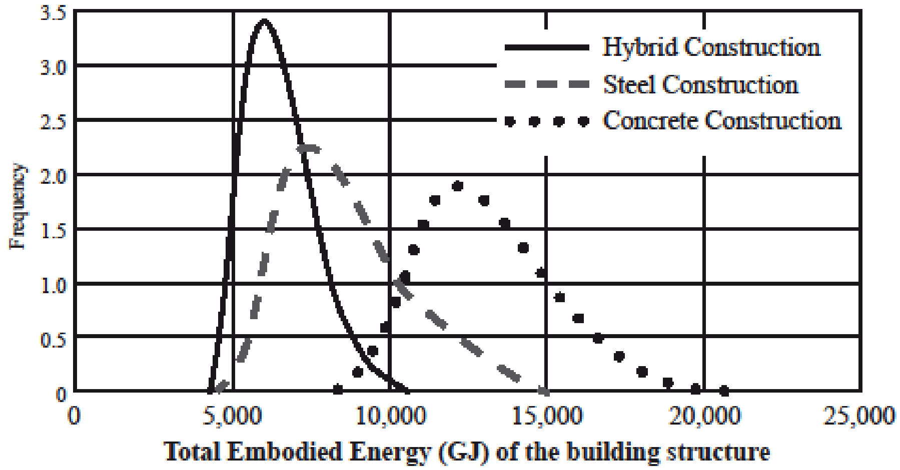

Figure 2. Correlation coefficient of the top three most influential input parameters for the three exemplary building structures.

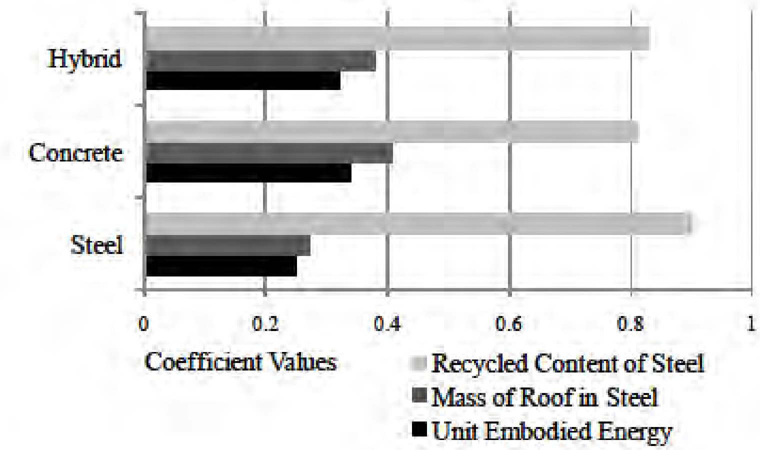

Table 1

Sub-categories and the possible points awarded under the materials and resources category [7].

Credit	Description	Points
1	Building Reuse	4
2	Construction Waste Management	2
3	Materials Reuse	2
4	Recycled Content	2
5	Regional Materials	2
6	Rapidly Renewable Materials	1
7	Certified Wood	1

Table 2

A breakdown of mass of the building structure.

(tonne)	Steel	Concrete	Hybrid
Steel - Wall	276	43	43
Steel - Roof	231	432	231
Concrete - Wall	-	1,440	1,440
Concrete - Roof	-	2,448	-

Table 3

Embodied energy according to [8] and [9].

Embodied Energy [MJ/kg]	A&W	H&J
Concrete	1.6	1.4
Virgin Steel	32.0	35.3
Recycled Steel	10.1	9.5

Table 4

Embodied energy of building materials and the range of uncertainty (due to reduction).

Building Materials	Embodied Energy [MJ/kg]	Possible Reduction in embodied energy
Concrete	1.6 ±10%	7% to 35% (◣ distributed)
Steel	33.7 ±10%	23.3% - 66.4% (■ distributed)

Table 5

Summary of total embodied energy of the three exemplary structures.

('000 GJ)	Steel	Concrete	Hybrid
Mean	9.0	13.6	6.8
St. dev.	2.0	2.4	1.1
90 % confidence interval	5.8 - 12.2	10.1 - 17.2	4.9 - 8.7
Minimum	4.9	8.0	4.9
Maximum	15.1	20.6	10.4

Table 6

LEED points achievable for new built under the material category for the three exemplary structures.

LEED points	Steel	Concrete	Hybrid
Credit 4 (assumed 32.7% recycled steel)	2	1	2
Credit 4 (assumed 93.3% recycled steel)	2	2	2
Credit 5	2	2	2