Impact of building material recycle or reuse on selected emergy ratios

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Abstract

While the emergy evaluation method has been used successfully in recycling processes, this area of application still requires further development. One of such is developing emergy ratios or indices that reflect changes depending on the number of times a material is recycled. Some of these materials may either have been recycled or reused continuously as inputs to a building, for example, and thus could have various impacts on the emergy evaluation of the building. The paper focuses on reuse building materials in the context of environmental protection and sustainable development. It presents the results of an emergy evaluation of a low-energy building (LEB) in which a percentage of input materials are from recycled sources. The corresponding impacts on the emergy yield ratio (EYR_B) and the environmental loading ratio (ELR_B) are studied. The EYR which is the total emergy used up per unit of emergy invested, is a measure of how much an investment enables a process to exploit local resources in order to further contribute to the economy. The ELR however, is the total nonrenewable and imported emergy used up per unit of local renewable resource and indicates the stress a process exhibits on the environment. The evaluation provides values for the selected ratios based on different recycle times. Results show that values of the emergy indices vary, even more, when greater amounts of material is recycled with higher amount of additional emergy required for recycling. This provides relevant information prioritizing the selection of materials for recycling or reuse in a building, and the optimum number of reuse or recycle times of a specific material.

Keywords: Emergy, Recycle, Low-energy building

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1. Introduction

Almost 40% of the world's consumption of materials converts to the built environment, and about 30% of energy use is due to housing (Pulselli et al., 2007). The building sector is the biggest consumption sector, before transports sector. As a result, there are ongoing research works to investigate how to significantly reduce the consumption of energy and material flows in the building industry. In effect, terms such as low-energy and passive house are used more frequently all over Europe.

Reuse and recycling of building material is a growing area of interest and concern in many parts of the world. Current practices and trends in the building material waste management are examined from a building life cycle standpoint or cradle to grave concept. To evaluate buildings and their environmental impacts more effectively, several tools and methods are adopted. These methods provide a list of indicators, based on objective values that compare buildings' performances and impacts to their environmental constraints. Some examples of these are the life cycle analysis (Guinée et al., 2001), the emergy analysis (Odum, 1996), the ecological footprint (Rees & Wackernagel, 2004), and the exergy analysis (Szargut et al., 1988). All of these assessments are needed to develop a comprehensive waste management plan for specific projects.

The use of construction waste management techniques which rely on recycle and reuse of materials have proven to have economic benefits for the construction industry (Kralj, 2007). Reuse is a means to prevent solid waste from entering the landfill, and increase the material, educational and occupational wellbeing of citizens by taking useful products discarded by those who no longer want them and providing them as inputs to the construction of buildings. In many cases, reuse reduces raw material inputs to a very large extent. This is important since a significant percentage of the total natural resources that are used in industrialized countries are exploited by the building industry (Peuportier et al., 1996). High quantities of raw material inputs for building construction results in high energy required for the extraction and processing of these materials.

Emergy evaluation has been widely applied in the evaluation of ecological systems, energy systems, and environmental impacts of processes, generating a large number of studies. Yet, despite such a wide debate, only a few studies have been produced concerning applications of emergy evaluation to building construction and to building materials. In most of these studies, emergy evaluation is employed as an environmental indicator for construction activities, building materials production and recycling (Buranakarn, 1998; Odum, 2002; Brown & Buranakarn, 2003; Huang & Hsu, 2003; Meillaud et al., 2005; Pulselli et al., 2007). Odum (2002) presents a broad approach to the relationships of building construction with materials circulation and energy hierarchy.

In the emergy approach, buildings are a storage of materials that is the sum of the inputs during the construction process. This storage loses emergy as building materials depreciate along time and become dispersed in the environment. New inputs by means of maintenance and repair actions keep the emergy flow into the building system.

Buranakarn (1998) and Brown & Burnakarn (2003) proposed a set of emergy indices to evaluate recycling patterns and recyclability of building materials. These emergy indices are suggested to measure the environmental benefits of three recycling trajectories: material recycle, by-product use, and adaptive reuse, i.e. recycling the material for a different purpose. The reuse option in the sense of reusing a product elsewhere was not considered in these studies. Emergy per mass is also pointed as a good indicator for recyclability. Buranakarn (1998) and Brown & Burnakarn (2003) also recognize that materials with higher emergy per mass are more suitable for being recycled by human systems due to their ‘quality’, and have more environmental impacts when released to the environment. In the context of an environmental approach, Huang & Hsu (2003) proposed a set of indicators based on emergy to measure the effects of construction in Taipei’s sustainability: (a) intensity of resource consumption; (b) inflow/outflow ratio; (c) urban livability; (d) efficiency of urban metabolism; and (e) emergy evaluation of urban metabolism. The relevance of emergy analysis for that study was in the fact that it enabled the consideration of biophysical value of resources to the economic system. Evaluation of main emergy flows of materials used due to urban construction provided both an understanding of their relative value and contribution to the ecological-economic system (urban construction is equivalent to 44% of the Emergy used in Taipei), and a measure of the ecological interface of rapid urban development (environmental load of construction waste generation and recycling opportunities).

Meillaud et al. (2005) applied emergy analysis to evaluate an experimental building of three stories containing faculty and students' offices and a workshop, built in 1981, by including environmental, economical, and information flows. By including information flows generated by building occupants to the analysis of the whole building system, it was possible to calculate the outputs generated by the building usage: emergy per educated student, emergy per publication, emergy per course and emergy per 'service'. The significance of emergy per unit was highlighted by Meillaud et al. (2005), since there were few available emergy per unit references for most commodities as inputs to a building.

Another application of emergy to building construction was published by Pulselli et al. (2007). The authors proposed a set of environmental indices to provide a basic approach to environmental impacts of buildings by accounting for the main energy and materials inflows within the building construction process, maintenance, and use:

(i) Building emergy per volume (Em-building volume): this represents the 'environmental cost' of the building;

(ii) Building emergy to money ratio (Em-building/money ratio): this represents the ratio of total Emergy used to money (seJ/€);

(iii) Building emergy per person (Em-buildings per person): this represents the rate of Emergy use of human systems with relation to buildings.

The proposed indices based on emergy accounting provide a framework for evaluating and comparing different building typologies, technologies and materials, regarding different manufacturing processes, maintenance, use, thermal efficiency and energy consumption. Pulselli et al. (2007) argue that buildings are like full emergy reservoirs (storage) that persists in time, and that emergy evaluation of a building highlights the durability of materials as a factor for sustainability. With reference to building materials, the most extensive Emergy study was developed by Buranakarn (1998) in order to identify recycling patterns. The author analyses several common materials.

The main aim of this paper is to extend the emergy based methodology to continuous matter reuse as devised by Amponsah et al. (2011) to a process. In fact, authors consider that the additional emergy (coming from each recycle matter) can be aggregated to the "classical" emergy evaluation which does not include any recycling. The different impacts this continuous reuse might have on the emergy yield ratio (EYR) and the environmental loading ratio (ELR) on the whole process require new definitions.

The rest of this paper is organized as follows: in section 2, relevant literature on emergy evaluation and its application in buildings are reviewed. The methodology developed by Amponsah et al. (2011) is outlined and defined in its specific context. In Section 3, a case study is presented on a low energy building that corresponds to the present construction standards in France. Section 4 presents a discussion and finally, section 5 concludes the paper.

2. Materials and methods

With reference to the work and formulae developed by Buranakarn (1998) and Amponsah et al. (2011) respectively, the output emergy of a system involving recycle inputs differs marginally from a similar system with 100% raw material inputs. Amponsah et al. (2011) further explained that the continuous recycling of a specific material due to the additional emergy required at each stage of recycle, impacts on the final output emergy of the system usually increasing the output emergy after each additional recycle.

As such, authors of the said paper pointed out that the specific emergy of any material e_m, containing a recycled part (or reused part) q_m, has a dynamic equation at discrete time, see equation (1), according to the specific total emergy inputs e_{mi} (emergy of raw material, fuel, goods and services etc.) without recycle, and the specific additional emergy needed for recycling (for reusing) e_{mc}. The sampling time for recycling is noted *Te* and the recycling number is noted n_m. As such the discrete time t is just equal to the product Te by n_m. For unitary amount of matter, one gets:

$$e_m(t) = e_{mi}(t)\,(1 - q_m(t)) + q_m(t)\,e_{mc}(t) + q_m(t)\,e_m(t-1) \quad (1)$$

The specific emergy of any matter at the n^{th} recycling is the sum of three terms: the specific emergy of raw material adjusted to its raw mass, the specific additional emergy adjusted to its recycled part and the part coming from the past within the matter itself adjusted to its recycled part. Amponsah et al. (2011) detailed that there is no double-counting in this decomposition and the pathway of the recycled matter is followed.

Equation (1) is in a general form. Assuming that the specific emergy inputs e_{mi} and the specific additional emergy needed for recycling e_{mc} and the recycled part q_m are independent of the discrete time, the specific emergy of matter containing a recycled part can be easily calculated by underlying the sum of a geometric series, noted ψ :

$e_m(1) = e_{mi} + e_{mc}\,q_m$ for the 1st Recycle, where the factor $\psi = q_m$ (2)

$e_m(2) = e_{mi} + e_{mc}(q_m + q_m^2)$ for the 2nd Recycle, where $\psi = q_m + q_m^2$ (3)

$e_m(3) = e_{mi} + e_{mc}(q_m + q_m^2 + q_m^3)$ for the 3rd Recycle, $\psi = q_m + q_m^2 + q_m^3$ (4)

$e_m(4) = e_{mi} + e_{mc}(q_m + q_m^2 + q_m^3 + q_m^4)$ for the 4th , $\psi = q_m + q_m^2 + q_m^3 + q_m^4$ and so on. (5)

Emergy evaluation classifies inputs into three categories: purchased, renewable, and non renewable. On the basis of these classes, some indicators can be computed in order to assess the sustainability of the use of resources (Lagerberg;1999):

- the emergy yield ratio (EYR) is the emergy of an output divided by the emergy of those inputs to the process that are purchased from the economy;
- the emergy investment ratio (EIR) is the purchased emergy from the economy (services and other resources) divided by the free emergy inflow from the environment.
- the environmental loading ratio (ELR) is the ratio of purchased and non-renewable indigenous emergy to free environmental emergy.

On this basis, Amponsah et al. (2011) extended these ratios to some dimensionless emergy indices for a single recycled material. Assuming that the emergy inputs e_{mi} and e_{mc} and the recycled part q_m are constant, these ratios are in connection with the pathway of the recycled material by the number of recycle times. Thus, by means of the geometric series:

$$EYR_m(q_m, n_m) = \frac{(e_{mi} + \psi\, e_{mc})}{(e_{miF} + \psi\, e_{mcF})} \qquad (6)$$

$$EIR_m(q_m, n_m) = \frac{(e_{miF} + \psi\, e_{mcF})}{(e_{miN} + \psi\, e_{mcN}) + (e_{miR} + \psi\, e_{mcR})} \qquad (7)$$

$$ELR_m(q_m, n_m) = \frac{(e_{miF} + \psi\, e_{mcF}) + (e_{miN} + \psi\, e_{mcN})}{(e_{miR} + \psi\, e_{mcR})} \qquad (8)$$

Where e_{mi} is the specific emergy of raw material use without recycle, and e_{mc} is the additional emergy needed for recycling. Their renewable part is indexed by *R*, the non renewable part by *N* and the purchased part by *F*, so $e_{mi} = e_{miF} + e_{miR} + e_{miN}$, see figure 1.

Figure 1: Emergy flows with additional emergy for recycling

Emergy source is noted SE.

If only one single matter with its associated pathway is considered, the total emergy for processing is increased by its additional emergy $\Delta E_{mc}(q_m, n_m)$:

$$\Delta E_{mc}(q_m, n_m) = m_m\, e_{mc}\, q_m \left(\frac{q_m^{n_m} - 1}{q_m - 1} \right) \qquad (9)$$

where m_m is the mass of the considered material, q_m is its mass fraction of recycle, n_m is its number of recycle, e_{mc} is the specific emergy required for 100% recycle.

For *M* recycled materials in a process indexed by *P*, such as building manufacturing, dimensionless ratios for the entire process can be defined as:

$$EYR_P = \frac{E_P^0 + \sum_{j=1}^{M} \Delta E_{jc}(q_j, n_j)}{E_{PF}^0 + \sum_{j=1}^{M} \Delta E_{jcF}(q_j, n_j)} \quad (10)$$

$$EIR_P = \frac{E_{PF}^0 + \sum_{j=1}^{M} \Delta E_{jcF}(q_j, n_j)}{E_{PN}^0 + E_{PR}^0 + \sum_{j=1}^{M} \left(\Delta E_{jcN}(q_j, n_j) + \Delta E_{jcR}(q_j, n_j)\right)} \quad (11)$$

$$ELR_P = \frac{E_{PF}^0 + E_{PN}^0 + \sum_{j=1}^{M} \left(\Delta E_{jcF}(q_j, n_j) + \Delta E_{jcN}(q_j, n_j)\right)}{E_{PR}^0 + \sum_{j=1}^{M} \Delta E_{jcR}(q_j, n_j)} \quad (12)$$

Where E_P^0 is the total emergy of the process without any recycle matter. E_{PF}^0, E_{PR}^0 and E_{PN}^0 are respectively its purchased, renewable and non renewable part. The additional emergy of the jth matter ΔE_{jc} is also decomposed into its three parts (purchased, renewable, and non renewable).

Buranakarn (1998) obtained the value for the main materials likely to be recycled in building construction:

- bricks: $e_{bi}(100\%) = 3.68E+09$ seJ/g, when reused $e_{bc}(100\%) = 2.6E+05$ seJ/g and when recycled $e_{bc}(100\%) = 4.8E+05$ seJ/g, see Amponsah (2011, p158-160)
- steel via the electric arc furnace process: $e_{si}(100\%) = 4.15E+09$ seJ/g, $e_{sc}(100\%) = 9.0E+07$ seJ/g, see Buranakarn (1998, p52)
- aluminium: $e_{ai}(100\%) = 1.27E+10$ seJ/g, $e_{ac}(100\%) = 6.4E+08$ seJ/g, see Buranakarn (1998, p60)
- plastic lumber: $e_{pi}(100\%) = 5.75E+09$ seJ/g, $e_{pc}(100\%) = 5.8E+08$ seJ/g, see Buranakarn (1998, p76)

3. Case Study

Low energy buildings involve the reduction of fossil fuel use such as oil, gas and coal, which enhances sustainable building and development. There are many ways to make a building energy-efficient: by high insulation, using building components resulting in less thermal bridges, buildings with good air tightness or by technical installations such as mechanical heat recovery ventilation, which also benefits the indoor climate (Andersson et al, 2006; Wargocki and Wyon, 2007).

The building studied is located in Theys (Isère) which is a small town 30 km far from Grenoble. It is defined by a net area of 155 m^2 calculated as the sum of the living area plus the garage area. It is intended for residential use. It comprises a basement, a ground floor and one other floor. The structure consists of a reinforced concrete frame with pillars and beams. The walls are made of concrete blocks with an internal insulation layer and gypsum plastering. The external wrapping is formed by two side walls (adjoining blocks), two facades (brickwork with cavities), an insulated basement. The upper ceiling is covered with mineral wool, under clay tiles roof. The house is heated by a natural gas boiler. The aluminum glass windows are double glazed with an overall heat transfer coefficient of 1.1 W/m^2 K. The annual heating consumption is of 50 kWh/m², corresponding to the upper limit for the French label low-energy building.

An inventory of inputs to the construction process with relative raw data has been drawn and the quantity of materials and their compositions are reported in a succession of steps that cover from the first to the last brick settled. Raw data (mass quantities) in the building metric computation has been reported in Table 1, and has been processed through the relative transformities and expressed in terms of solar emergy joules. References for transformities used in the table are from: Odum et al. (2000); Brown and Buranakarn (2003); Meillaud et al. (2005); Odum (1996).

Table 1. Emergy evaluation Table

Emergy flows have been reported relative to the materials used to build each component and structural part. In this case, human labor is not considered. The composition and the percentage of the main building materials used, assists in knowing the main material inputs for the construction of the building. The subsequent emergy results enable us to make a list of building materials based on their ‘environmental cost’ (in terms of seJ) that depends on both their quantity and their transformity (quality).

Major comments on table 1 are the following:

- Line 1, the sun primarily serves as a source of light for site workers during the daytime of work. The sun also helps in drying material used in construction (such as, concrete, mortar, paints, etc...), see Pulselli et al. (2007) and Meillaud et al. (2005).
- The electricity breakdown used, come from the energy mix in France, see website U.E. 2007. Since electric energy is purchased to national grid, authors chose to make no distinction from the source.
- The renewable emergy part of whole building construction is considered as the sum of sun and water emergy. Its purchased emergy part is considered as the sum of fuel and electricity emergy.
- In Table 1, the value of transformities corresponds to a process with no recycling. Without any recycled material, the total emergy for building manufacturing, noted E_B^0, is 7.11E+16 seJ, sharing in its renewable inputs (line1&2) E_{BR}^0, in its non renewable inputs (line 3-65) E_{BN}^0 and in its purchased inputs (line 66-70) E_{BF}^0. The index B refers to building construction, the process studied in the case study, and the exponent 0 refers to any recycled material.
- It is observed that concrete takes about 74% in mass of the entire material inputs of the building followed by bricks.

Emergy values of the main individual materials are also presented in Fig. 2. It can again be observed that concrete still remains a significant material not only in quantity use but also in terms of its emergy input to the building. This is because although concrete does not have a too high transformity value, it is used in a very large proportion in the construction and thus it becomes responsible for a large share of the total emergy (65%) of the total material input.

Figure 2. Emergy inputs of main raw materials in constructing the building

Fig. 2 shows, however, that limestone (which has the third largest input quantitatively) falls out when emergies are considered. This is explained by the low transformity value (1.68E+09 seJ/kg) of limestone. Inversely, PVC, though slightly low in consumption, have a high value of transformity (9.86E+12 seJ/kg). This makes PVC a good choice for recycling or reuse, since it has a high embodied energy per unit mass. Nevertheless, PVC cannot have a significant effect on the emergy of the building construction.

4. Discussion

First, authors consider only one matter, the bricks, since they were found to be the second most used material in the construction of the building (after concrete), accounting for about 19% of the total material input. Though it might not be the best example of a reusable or recyclable material in building, compared to PVC, steel etc, the idea is to illustrate the developed procedure of emergy evaluation. The emergy of the building is thus re-evaluated, taking into account different scenarios. As such, emergy for sorting, collection and transportation to the recycling plant is considered, in addition to the emergy for the plant process. This emergy adds up to give the additional emergy of bricks recycling (ΔE_{bc}). For this building, the specific emergy of bricks (with a total mass of 3767 kg) is $e_{bc} = 2.6E+05$ seJ/g if 100% reused and $e_{bc} = 4.8E+05$ seJ/g if 100% recycled. Numerical application gives an emergy of 9.9E+11 seJ when reused and 1.81E+12 seJ when recycled. This is then multiplied by the quantity (q_b= 30% in this case) of recycled (or reused) bricks. Authors assume that this additional emergy $\Delta E_{bc}(q_m, n_m)$, corresponds mainly to collection and separation, and is incorporated only in purchased inputs $\Delta E_{bcF}(q_m, n_m)$. Equation (10) begins:

$$EYR_B = \frac{E_B^0 + \Delta E_{bcF}(q_b, n_b)}{E_{BF}^0 + \Delta E_{bcF}(q_b, n_b)} \qquad (13)$$

- The result for the first reuse (q_b e_{bc}) is added up to the initial emergy of the building (ref. Table 1) 7.1E+16 seJ giving an emergy difference of 5.4E+11 seJ. Results for recycled bricks are proposed in Table 2, in the case of 30% recycle rate of bricks (q_b) and for different number of times of recycling.

- For the first reused bricks, the numerical application gives the emergy difference of 2.99 E+11 seJ. Results for reused bricks are proposed in Table 3 always in the case of 30% reuse part and for different number of times of reuse.

This is continued for different number of times of recycle and for different quantities to assess the various impacts on the emergy analysis of the building (refer to equations 2 to 5).

Table 2. Emergy results for bricks recycling for different recycling times.

Table 3. Difference in emergy involving a part of material recycle and initial emergy of building for reuse of bricks (e.g. in concrete mix)

The same scenario is used to analyze the various effects on the emergy yield ratio. It is seen from the results presented that the EYR decreases with respectively an increase of recycling time in Fig. 3a and reusing time in Fig 3b. This is explained by the increase of additional goods and services purchased to aid in the recycling process. Figs. 4a and 4b show respectively the potential impact of recycled bricks (Figure 4a) and reused bricks (Figure 4b) on the emergy yield ratio (EYR_B) of the building. Without any recycling EYR_B is the ratio of the total emergy for building construction (7.11 E+16 seJ) to the emergy part purchased from economy (1.98 E+13 seJ). Numerical application gives 3.59E+3. This value means that the purchased emergy part is low. As presented in table (2) for recycling or table (3) for reusing, the additional emergy $\Delta E_{bc}(q_m, n_m)$ is about 1% of E_{BF}^{0} so the bricks recycling, or the bricks reusing, has a low impact on the ratio EYR_B for the building construction, see Figs 3a and 3b. Since bricks reusing emergy is approximately half the one for recycling, the impact of reusing on EYR_B is lower than the one for recycling. The greater the number of recycling (or reusing) is, the lower the EYR_B is and consequently the proportional part of purchased economy increases, see Figs 4a and 4b.

Common sense has it that both recycling and reusing tend toward sustainability. Hence, Ulgiati et al. (2004) proposed a path of emergy allocation in which the emergy rules not violated. In this, the emergy invested in the treatment and recycling process should be assigned to the recycled resource. As such, the proposal suggests that wastes only bear the additional emergy inputs needed for their further processing. Ulgiati et al. (2004) then amounted to 'reseting' the emergy content in recycling processes to eliminate the problem of cumulative emergy.

Figure 3. Impact of 30% (constant rate) continuous bricks recycle (a) and reuse (b) on EYR_B of the building

Figure 4. Impact of different recycling rates for continuous bricks recycle (a) and reuse (b) on EYR_B of the building

Authors consider one additional material, the plastic, its mass is 171 kg and its specific recycle emergy is 5.8 E+08 seJ/g. For 30% of recycled part, the value of the first recycling (2.98 E+13 seJ corresponding to the product of specific transformity 5.8E+13 seJ/kg by its mass 171 kg and by its recycle part 30%) is greater than the purchased emergy for the building construction (1.98 E+13 seJ). So the impact of plastic recycling is very significant on EYR_B, see Fig. 5. Fig.6 shows the impact of recycled plastic on the emergy yield ratio (EYR_B) of the building.

Figure 5. Impact of 30% (constant rate) continuous plastic recycle on EYR_B of the building

Figure 6. Impact of different recycling rates for continuous plastic recycle on EYR_B of the building

As can be seen in the results of the EYR_B, ignoring the impact of material reuse or recycling leads to the loss of significant information. Extending the traditional EYR_B to include the recyclable values from the additional emergy needed for recycling, increases the value associated to the purchased goods and services and thus reduces the EYR_B. It is observed that EYR_Bs are lower in higher recycling times. For instance, the difference between EYR_B for a 1st recycle and a 5th recycle is quite significant (3.92E+01). This is due to the significant changes in the additional emergy amounts needed for the cycle of material recycling or reuse.

In the case only one material is recycled (or reused), bricks for example, the emergy loading ratio for building construction ELR_B is defined as:

$$ELR_B = \frac{E_{BF}^0 + E_{BN}^0 + \Delta E_{bcF}(q_b, n_b)}{E_{BR}^0} \quad (14)$$

ELR_B is increasing with both the recycle part (or reuse part), and the number of cycles. A higher ELR_B suggests that investing in waste management causes more environmental stress. This is due to the fact that the purchased inputs from the economy needed for recycling, or resuing, increase.

Figure 7. Impact of different recycle rates (a) and reuse rates (b) for continuous bricks recycle on ELR_B of the building

Fig.7a and 7b show that the developed methods if utilized would serve as an extension to quantify and interpret the attributes of systems with percentages of respectively recycled inputs and reused inputs, with important implications in comparative decision making.

Before conclusion, authors would like to emphasize on two major points

- Equations (10-12) have been introduced to study the impact of several recycled materials (or reused) with different parts and at different numbers of recycling (or reusing) on emergy assessment of a process. In this paper, it does not worth it to multiply numerical applications. It is possible to mix the assessment of bricks and plastic recycling, and so on…. This paper provides the method.
- It is very important to know the industrial process for recycling (or reusing), in other words the pathway of the recycled (or reused) material. In this paper, authors have considered that this industrial process is based on collection and

separation, and have allocated this additional emergy as a purchased emergy. If one wants to allocate it to the product itself, by increasing its transformity in emergy table (as Table 1), then the additional emergy is considered in the non renewable part in the emergy assessment of a process. In this case of building construction, recycling and reusing would not have any impact on the ratios EYR_B and ELR_B because the value E_B^0 is so significant that the additional emergy is negligible.

5 Conclusion

Emergy can be used successfully to evaluate systems with a fraction of its input materials derived from recycle sources, by effectively following the pathway of the material during the entire process (avoiding double counting). In this paper the methodology proposed by Amponsah et al. (2011) is applied and exemplified in the emergy evaluation of a low energy building in France. The evaluation results reveal significant impacts on the emergy yield ratio (EYR_B) and the emergy loading ratio (ELR_B) of the building having a fraction of its input materials from recycled sources. The proposed methodology is important to provide the link between the emergy evaluation method and the hidden information in recycling materials severally. This is very useful for evaluating and improving systems which often have recycled inputs, to compare the usefulness of using raw material inputs or recycled inputs. Moreover, it enables an investigator to select optimum levels of recycling (amount to recycle and number of times of recycle) to achieve greater results towards sustainability. From the case study, every process in which a fraction of inputs can be traced to recycle sources, can be evaluated simply by applying the factor ψ. In this way the difficulty of recalculations is somehow reduced, since the factor could easily be selected depending on the time of recycling (1st, 2nd, 3rd etc recycling). The results of EYR_B and ELR_B substantiate the need for the continuous development of emergy as a useful analytical tool, due to its ability to account for the contribution of ecosystems to economic activity. Furthermore, emergy provides useful indicators for evaluating the ecological feasibility as well as sustainability of construction processes and buildings. The improved indicators proposed in this work provide a conceptually sound basis to quantify the impacts of recycling or reuse of materials in a typical low energy building. The calculated indicators were shown to be consistent with the notion that investing in waste management must be expected to lead to less environmental stress largely dependent on the input materials either from renewable, non renewable or purchased sources. A good balance of these would enhance sustainability.

In future works, it could be interesting to consider the emergy assessment for automotive since the part of recycling is rather important in this sector (up to 90%). The consumer goods sector should also be studied through the emergy assessment as it is a non-negligible natural-resources consumption (e.g. packaging: metal cans, glass cans, paper, cardboard...).

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LIST OF FIGURES

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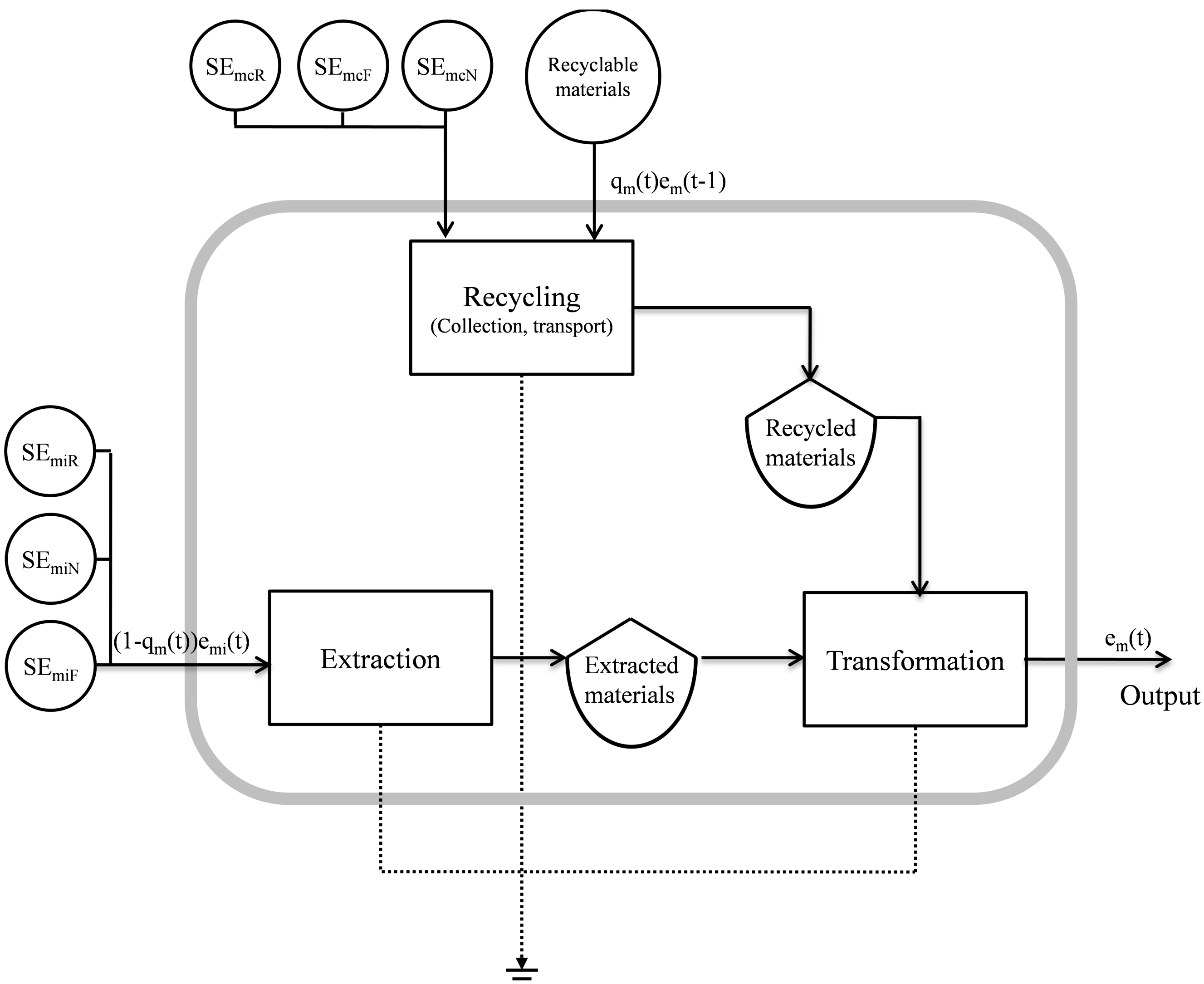
Figure 1



SE_mcR
SE_mcF
SE_mcN
Recyclable materials
q_m(t)e_m(t-1)
Recycling
(Collection, transport)
Recycled materials
SE_miR
SE_miN
SE_miF
(1-q_m(t))e_mi(t)
Extraction
Extracted materials
Transformation
e_m(t)
Output

Figure 2

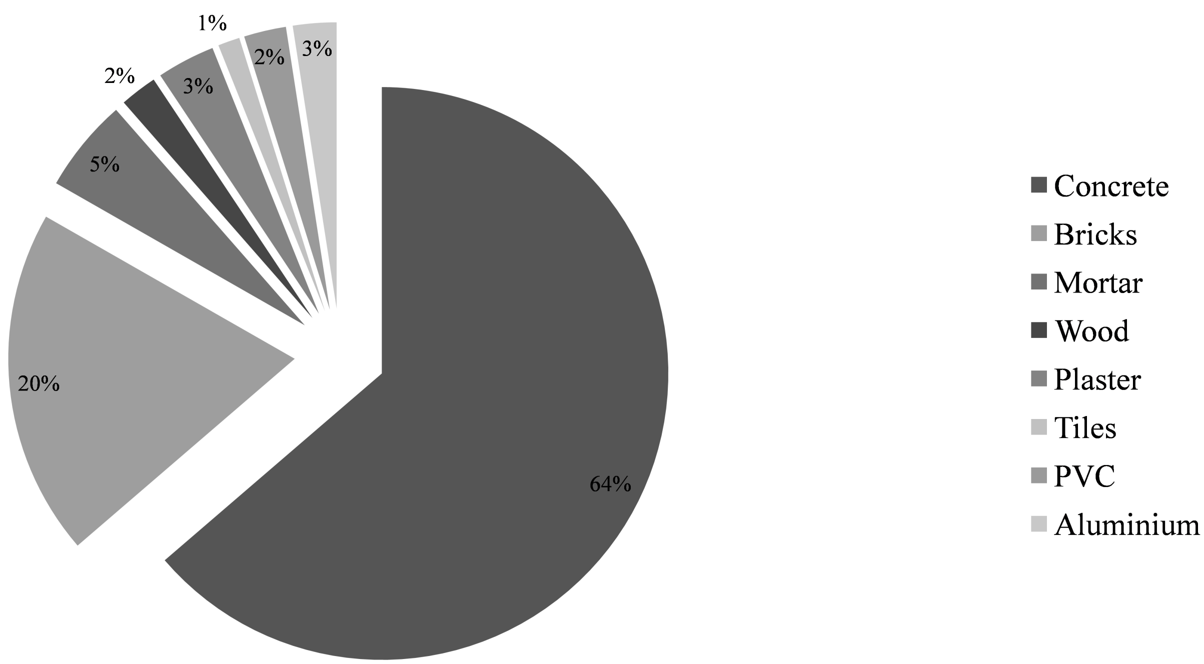

1%
2%
3%
2%
3%
5%
20%
64%
Concrete
Bricks
Mortar
Wood
Plaster
Tiles
PVC
Aluminium

Figure 3a

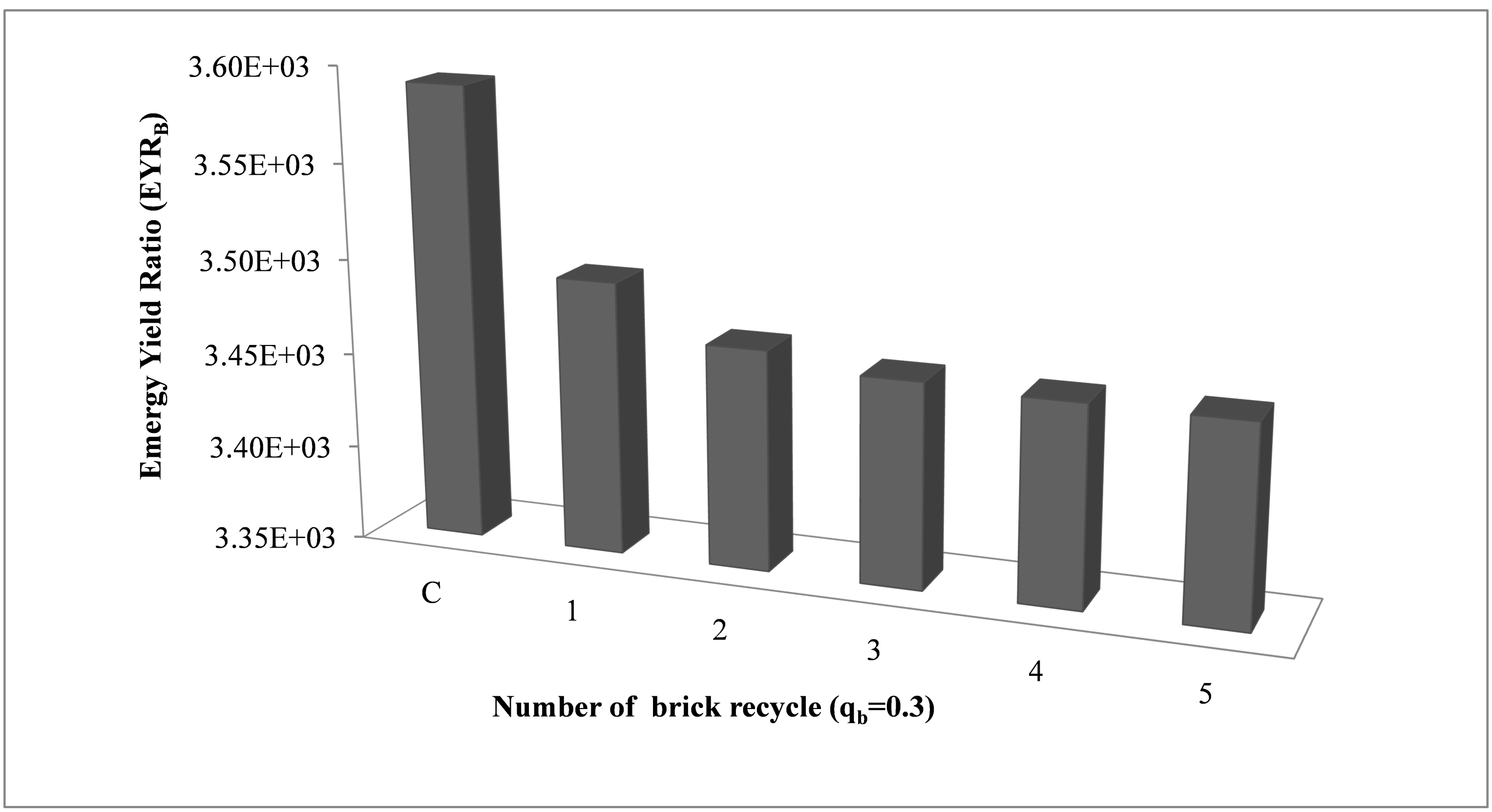
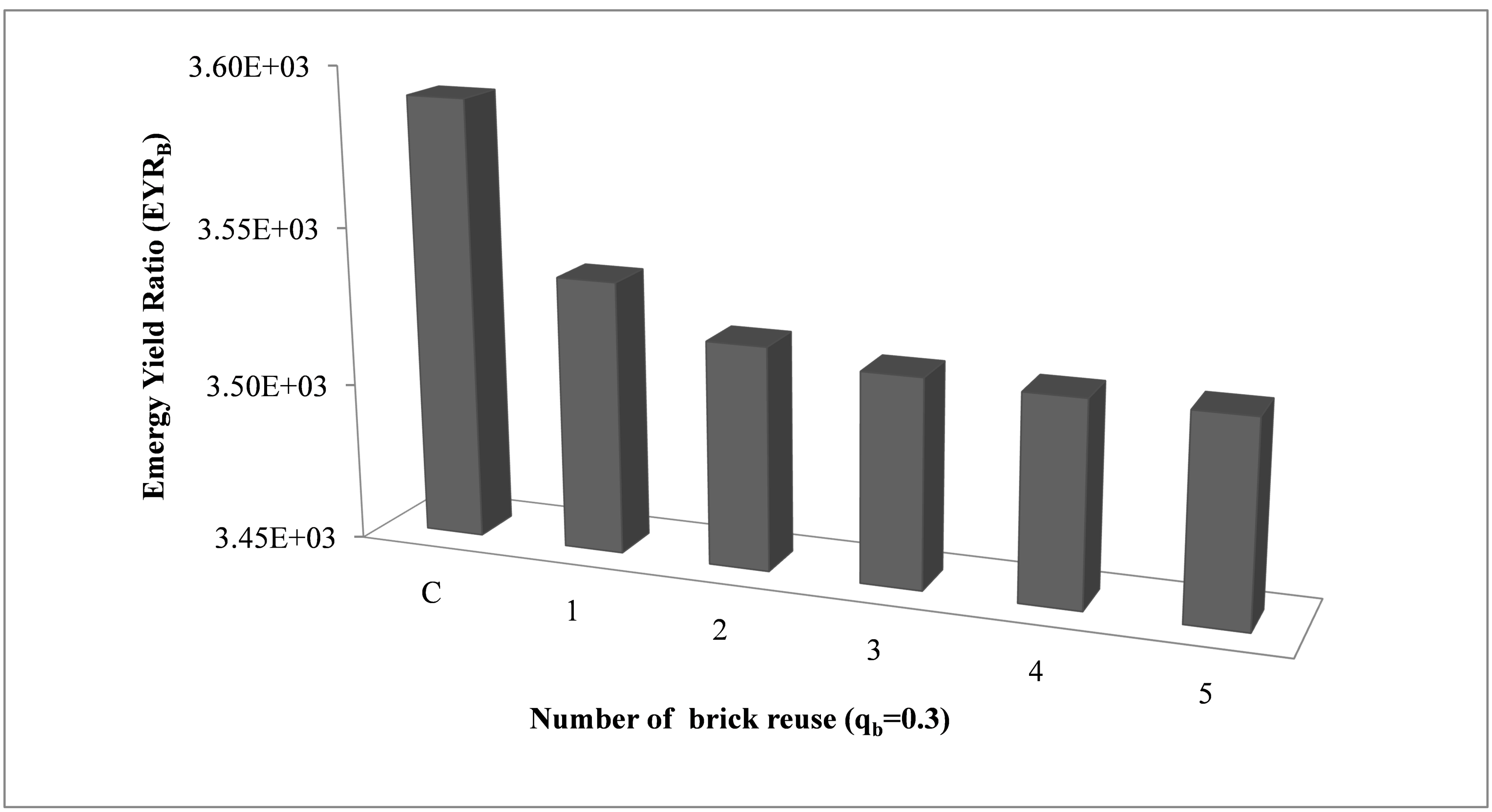
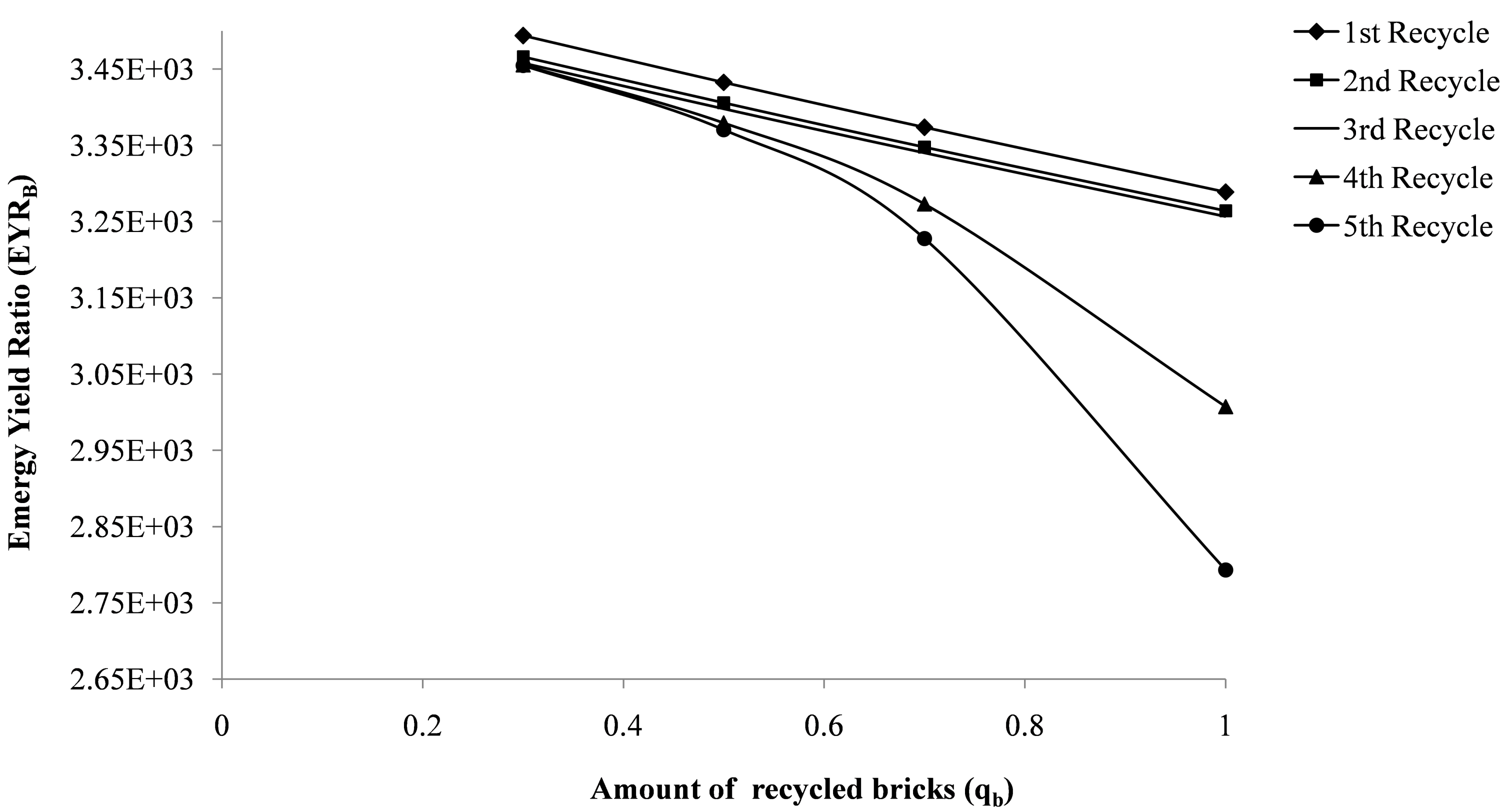

3.60E+03
3.55E+03
3.50E+03
3.45E+03
3.40E+03
3.35E+03
Emergy Yield Ratio (EYR_B)
C
1
2
3
4
5
Number of brick recycle (q_b=0.3)

Figure 3b



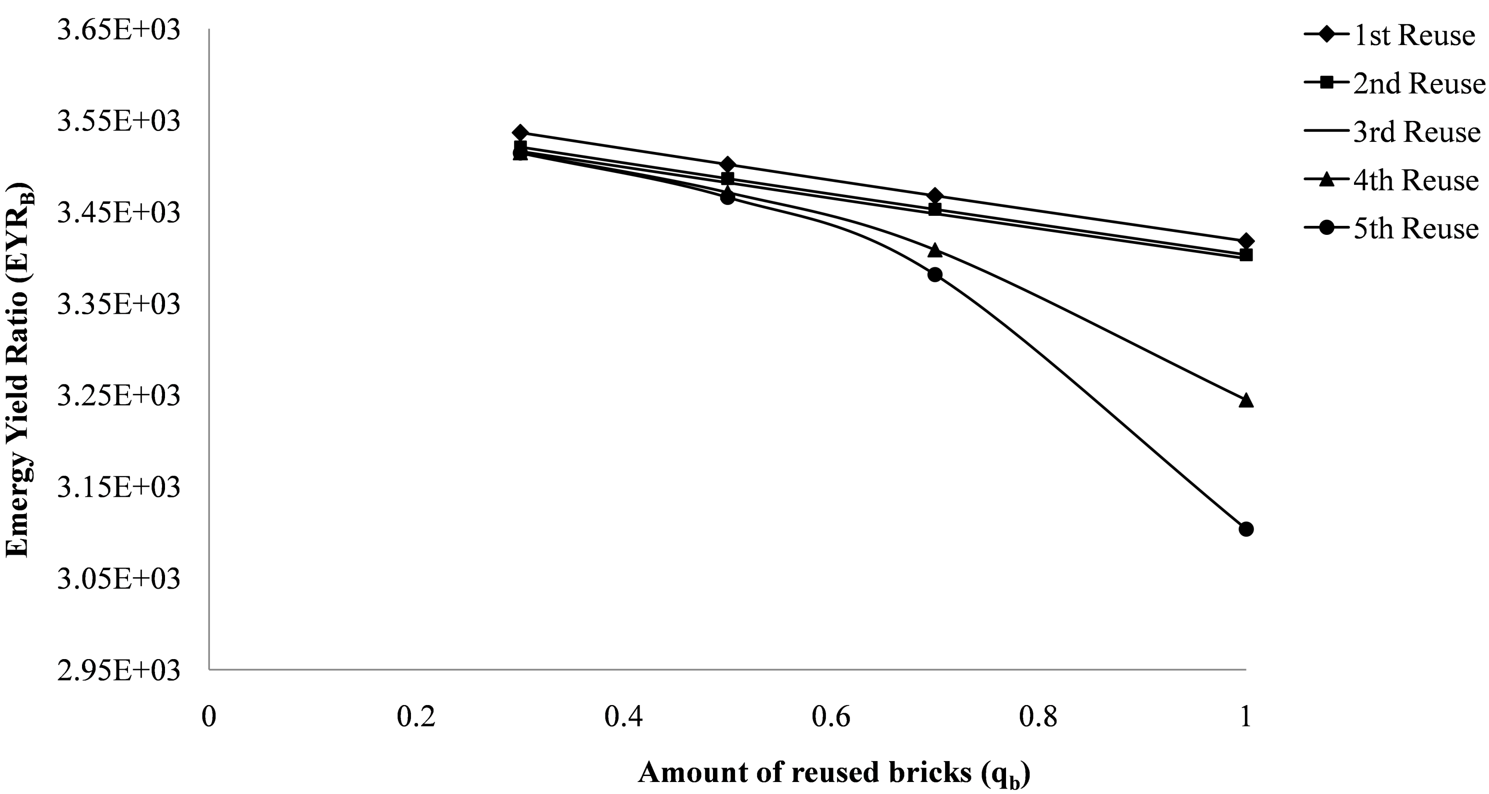
3.60E+03
3.55E+03
3.50E+03
3.45E+03
Emergy Yield Ratio (EYR$_B$)
C
1
2
3
4
5
Number of brick reuse (q$_b$=0.3)

Figure 4a



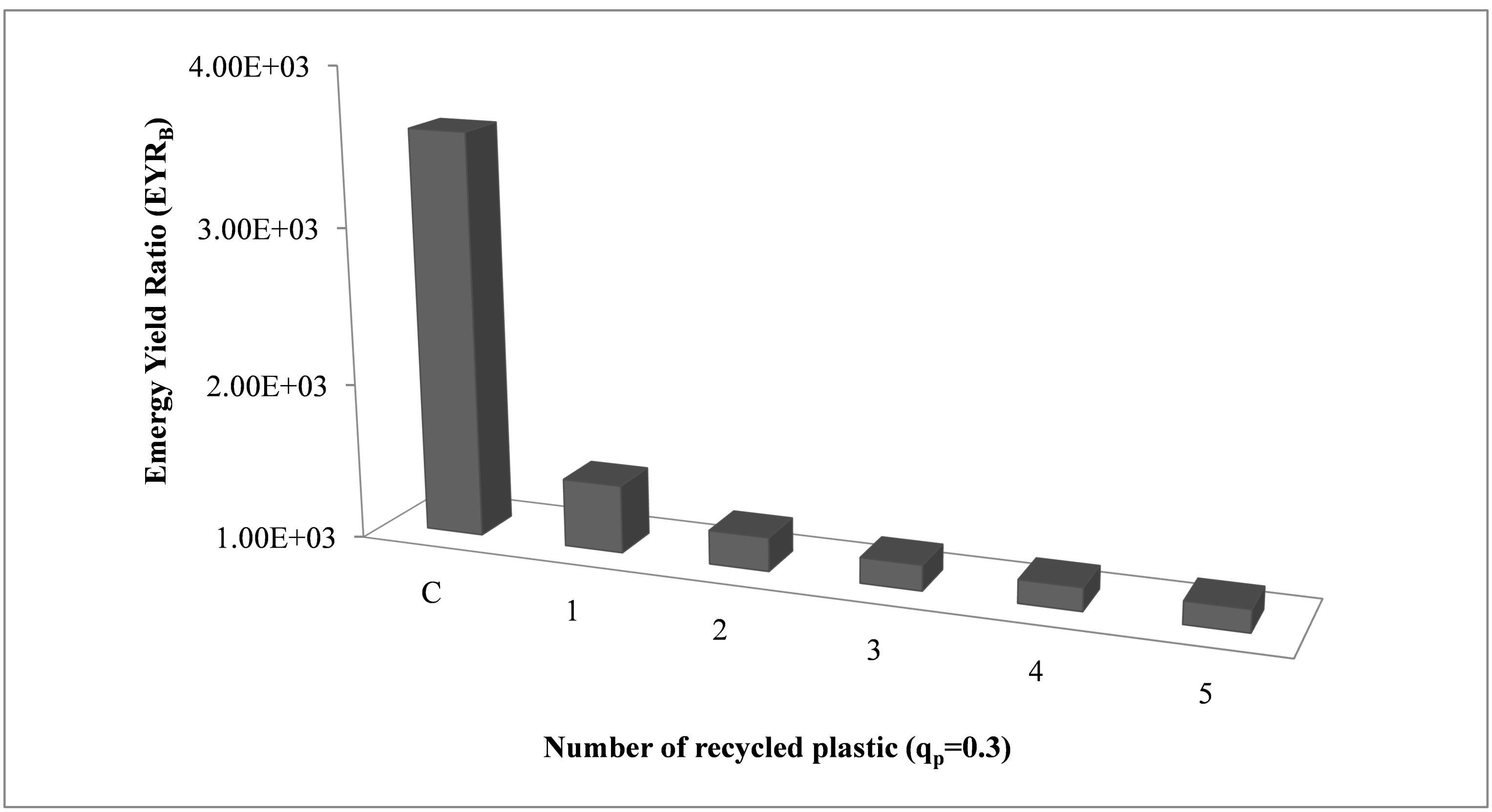
1st Recycle
2nd Recycle
3rd Recycle
4th Recycle
5th Recycle
Emergy Yield Ratio (EYR_B)
3.45E+03
3.35E+03
3.25E+03
3.15E+03
3.05E+03
2.95E+03
2.85E+03
2.75E+03
2.65E+03
0
0.2
0.4
0.6
0.8
1
Amount of recycled bricks (q_b)

Figure 4b



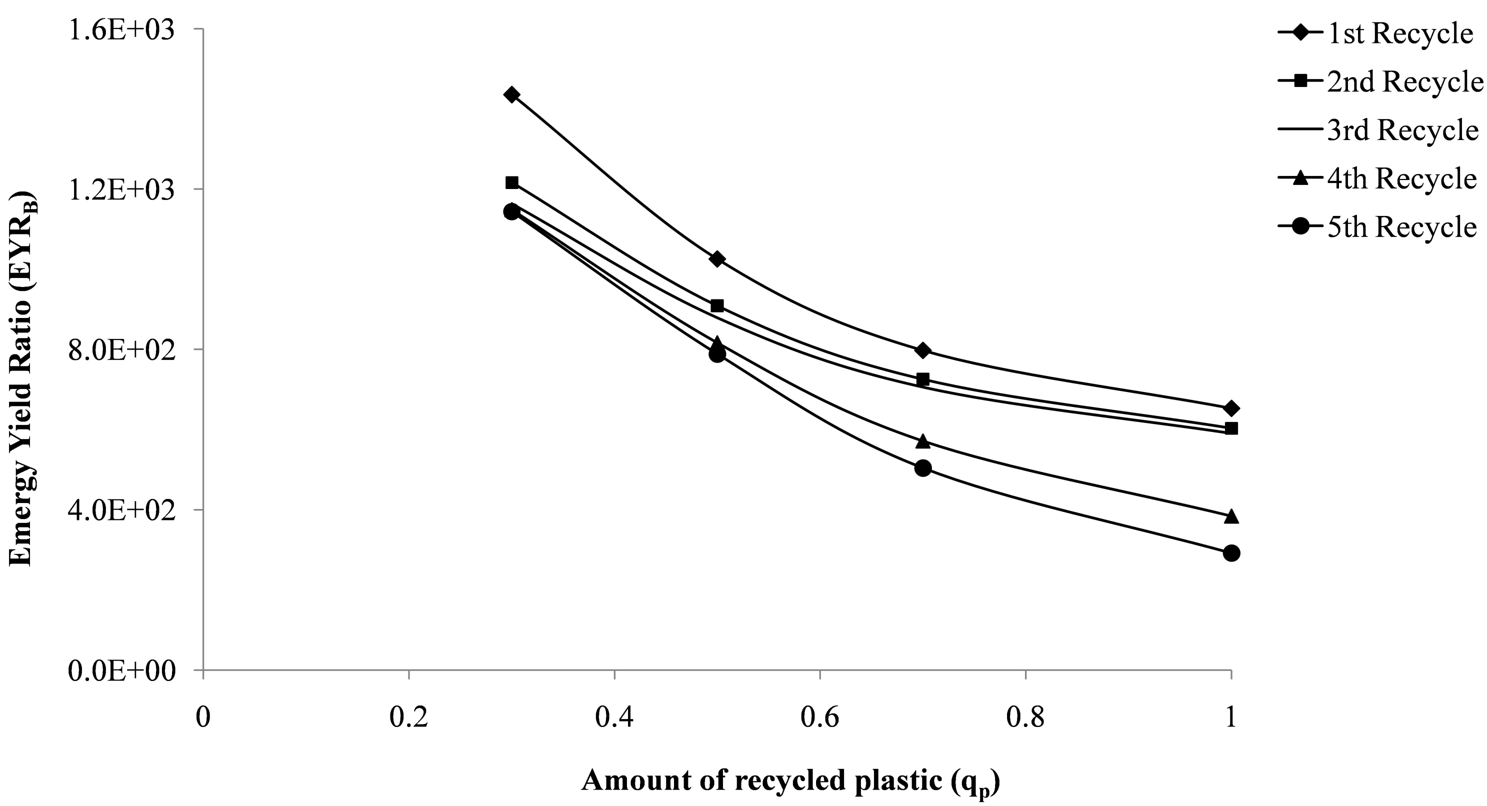
3.65E+03
3.55E+03
3.45E+03
3.35E+03
3.25E+03
3.15E+03
3.05E+03
2.95E+03
Emergy Yield Ratio (EYR$_B$)
0
0.2
0.4
0.6
0.8
1
Amount of reused bricks (q$_b$)
1st Reuse
2nd Reuse
3rd Reuse
4th Reuse
5th Reuse

Figure 5



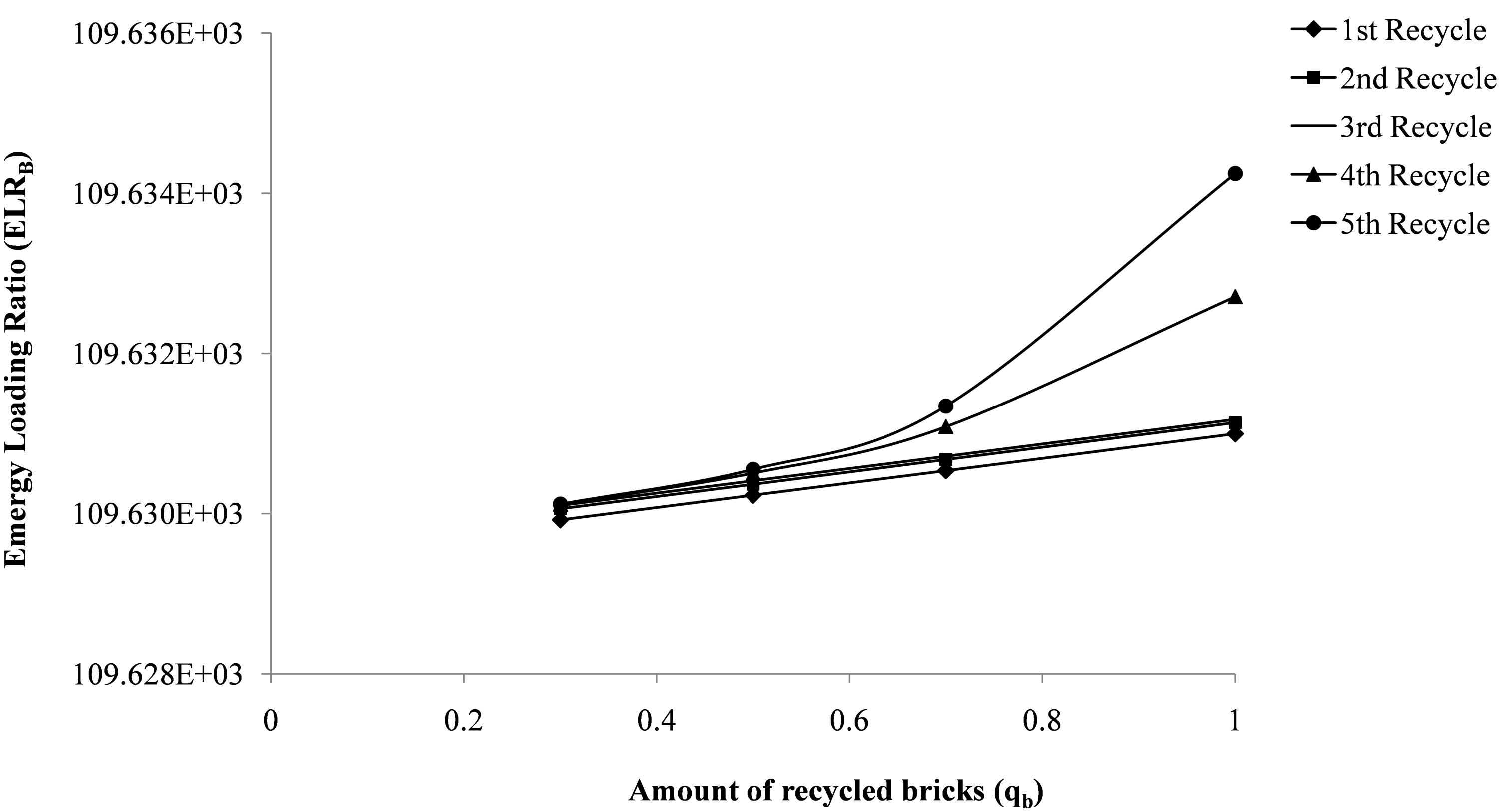
4.00E+03
3.00E+03
2.00E+03
1.00E+03
Emergy Yield Ratio (EYR_B)
C
1
2
3
4
5
Number of recycled plastic (q_p=0.3)

Figure 6



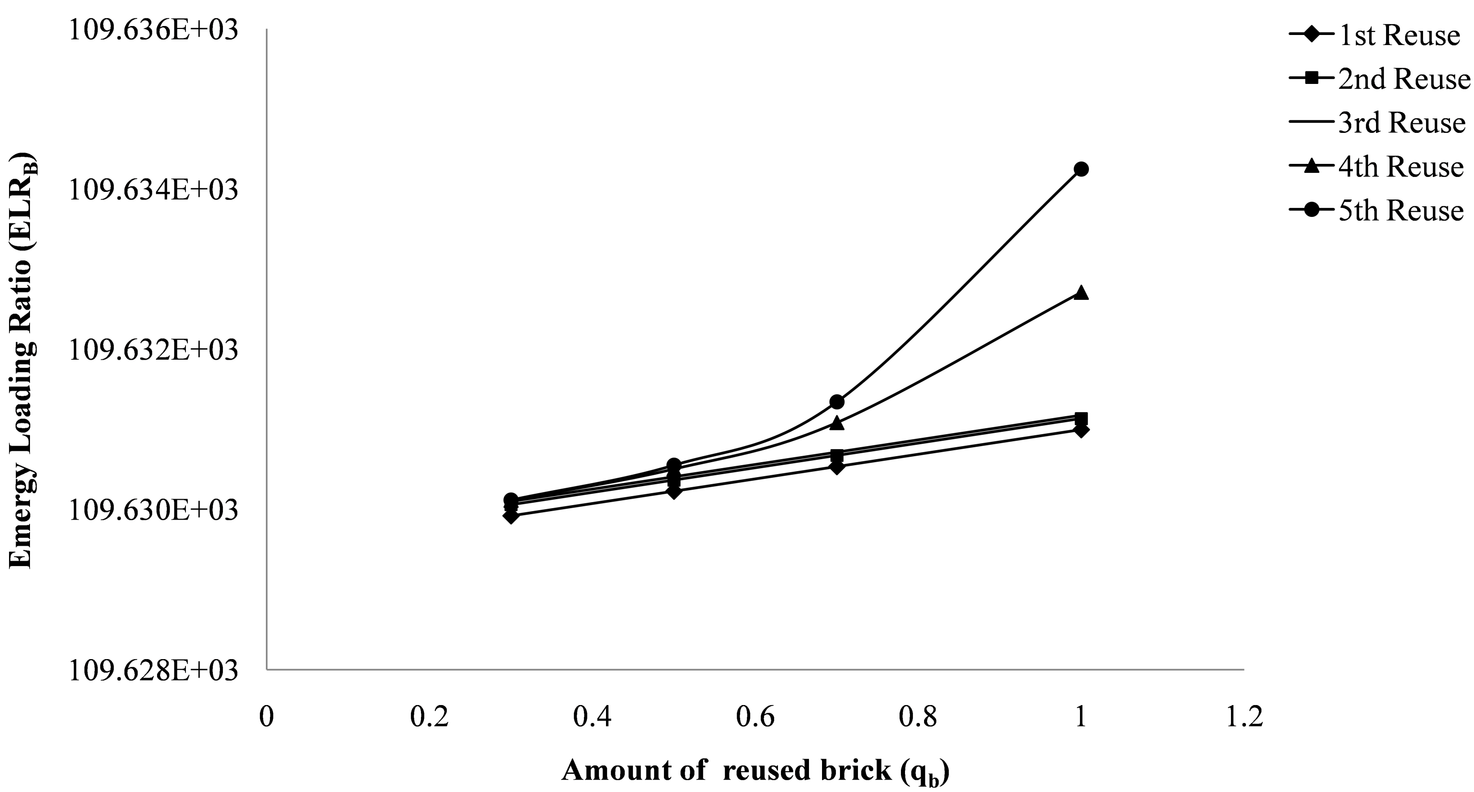
1.6E+03
1.2E+03
8.0E+02
4.0E+02
0.0E+00
Emergy Yield Ratio (EYR_B)
0
0.2
0.4
0.6
0.8
1
Amount of recycled plastic (q_p)
1st Recycle
2nd Recycle
3rd Recycle
4th Recycle
5th Recycle

Figure 7a



109.636E+03
109.634E+03
109.632E+03
109.630E+03
109.628E+03
0
0.2
0.4
0.6
0.8
1
Emergy Loading Ratio (ELR_B)
Amount of recycled bricks (q_b)
1st Recycle
2nd Recycle
3rd Recycle
4th Recycle
5th Recycle

Figure 7b



109.636E+03
109.634E+03
109.632E+03
109.630E+03
109.628E+03
Emergy Loading Ratio (ELR$_B$)
0
0.2
0.4
0.6
0.8
1
1.2
Amount of reused brick (q$_b$)
1st Reuse
2nd Reuse
3rd Reuse
4th Reuse
5th Reuse

Table1

1 Note	2 Item	Density (kg/m³)	Volume (m³)	3 Raw data	Unit	4 Transformity (seJ/unit)	5 Ref.	6 Emergy (seJ)
	Renewable Inputs							
1	Sun			6.19E+11	J	1.00E+00	a	6.19E+11
2	water	1000	614.52	6.15E+05	kg	4.80E+04	a	2.95E+10
	Non Renewable Inputs							
	Basement (floor)							
3	concrete	1500	5.1	7718	kg	1.81E+12	b	1.40E+16
4	Soft limestone	1500	1.0	1544	kg	1.68E+09	f	2.59E+12
5	Heavy concrete	2300	0.5	1183	kg	1.81E+12	b	2.14E+15
	Ground floor (floor)							
6	concrete	1300	0.8	1071	kg	1.81E+12	b	1.94E+15
7	heavy concrete	2300	0.2	474	kg	1.81E+12	b	8.58E+14
8	Polyurethane effisol	35	0.3	11	kg	8.85E+12	c	9.57E+13
9	Mortar	2000	0.3	618	kg	3.31E+12	c	2.05E+15
10	Tiles	2300	0.1	118	kg	3.68E+12	c	4.36E+14
	Underground Wall							
11	Concrete	1500	5.2	7803	kg	1.81E+12	b	1.41E+16
12	Heavy concrete	2300	1.0	2393	kg	1.81E+12	b	4.33E+15
	Wall (on the west)							
13	Light wood	500	0.2	110	kg	2.40E+12	f	2.64E+14
14	Wooden fibre	40	0.6	23	kg	2.40E+12	f	5.64E+13
15	Bricks	741	2.8	2040	kg	3.68E+12	c	7.51E+15
16	Plaster	1400	0.1	206	kg	3.29E+12	d	6.76E+14
17	Wooden panel	120	0.02	2	kg	2.40E+12	f	5.74E+12
18	plaster	1200	0.02	24	kg	3.29E+12	d	7.87E+13
	Wall coating							
19	Lime plaster	1400	0.1	73	kg	3.29E+12	d	2.41E+14
20	Bricks	741	1.0	727	kg	3.68E+12	c	2.67E+15
21	Plaster	1400	0.1	73	kg	3.29E+12	d	2.41E+14
	Plastering							
22	Plaster	1400	0.01	14	kg	3.29E+12	d	4.68E+13
23	Concrete blocks	1300	0.10	132	kg	1.81E+12	b	2.39E+14
24	Lime plaster	1400	0.01	14	kg	3.29E+12	d	4.68E+13
	Wall (East)							
25	Porothermn bricks30	762	0.3	196	kg	3.68E+12	c	7.21E+14
26	Bricks 10.7 cm	1700	0.1	153	kg	3.68E+12	c	5.63E+14
27	Bricks 10.5 cm	1700	0.1	153	kg	3.68E+12	c	5.63E+14
	Wall (North)							
28	Concrete	1500	1.8	2694	kg	1.81E+12	b	4.88E+15
29	Bricks	741	0.7	499	kg	3.68E+12	c	1.84E+15
30	Wooden fibre	40	0.1	3	kg	2.40E+12	f	6.90E+12
31	Light wood	500	0.1	27	kg	2.40E+12	f	6.47E+13
	Intermediate Floor							
32	Plaster	1500	0.1	154	kg	3.29E+12	d	5.07E+14
33	Concrete	1300	0.6	802	kg	1.81E+12	b	1.45E+15
34	Heavy concrete	2300	0.2	473	kg	1.81E+12	b	8.56E+14
35	Polystyrene extrude	35	0.3	11	kg	8.85E+12	c	9.55E+13
36	Mortar	2000	0.3	514	kg	3.31E+12	c	1.70E+15
37	Tiles	2300	0.1	118	kg	3.68E+12	c	4.35E+14
	Room Partitioning							
38	Plaster	1200	0.1	74	kg	3.29E+12	d	2.44E+14
39	Wooden fibre	40	0.5	20	kg	2.40E+12	b	4.75E+13
40	Plaster+cellulose	1200	0.1	74	kg	3.29E+12	d	2.44E+14
41	Concrete	600	0.1	73	kg	1.81E+12	b	1.33E+14
	Roof rafters							
42	Terracotta	1900	0.1	153	kg	1.68E+09	b	2.57E+11
43	Air space	1	0.0	0.04	kg	6.97E+12	a	2.80E+11
44	Wooden fibre	40	0.5	19	kg	2.40E+12	b	4.63E+13
45	Wooden board	800	0.1	43	kg	2.40E+12	b	1.03E+14

1 Note	2 Item	Density (kg/m³)	Volume (m³)	3 Raw data	Unit	4 Transformity (seJ/unit)	5 Ref.	6 Emergy (seJ)
	Upstairs Roofing							
46	Terracotta	1900	0.1	165	kg	1.68E+09	b	2.78E+11
47	Air space > 1.3 cm	1	0.0	0.04	kg	6.97E+12	a	3.03E+11
48	Wooden fibre	40	0.5	21	kg	2.40E+12	b	5.01E+13
49	Light wood	800	0.1	46	kg	2.40E+12	b	1.11E+14
50	Interior wooden door	750	0.06	48	kg	2.40E+12	b	1.15E+14
60	Double glass window for external door 4,16,4 argon	2700	0.03	82	kg	2.13E+13	c	1.74E+15
61	Glass Window	2700	0.02	44	kg	1.41E+12	e	6.18E+13
62	External wooden door	750	0.06	41	kg	2.40E+12	b	9.91E+13
63	metallic gate	7874	0.01	48	kg	8.55E+08	a	4.12E+10
64	Drainage system (PVC)			171	kg	9.86E+12	c	1.69E+15
65	Staircase (wood)			300	kg	2.40E+12	b	7.20E+14
	Purchased Inputs							
66	Fuel (Transports)			1.74E+08	J	1.13E+05	h	1.96E+13
	Energy consumed (Electricity use on site)							
67	Nuclear (78%)			8.88E+05	J	2.00E+05	g	1.78E+11
68	Hydro (14%)			1.59E+05	J	8.00E+04	a	1.28E+10
69	Natural gas (4%)			4.56E+04	J	4.80E+04	a	2.19E+09
70	Coal (4%)			4.56E+04	J	4.00E+04	a	1.82E+09
	Total emergy for building manufacturing							7.11E+16

[a] Odum et al. (2000); [b] Simoncini (2006); [c] Brown and Buranakarn (2003); [d] Meillaud et al. (2005); [e] Odum et al. (1987); [f] Odum (1996); [g] Brown and Arding (1991); [h] Bastianoni et al. (2005)

Table 1. Emergy evaluation Table

Table 2

	ψEc, seJ
Recycling	
1st	5.4E+11
2nd	7.1E+11
3rd	7.6E+11
4th	7.7E+11
5th	7.8E+11

Table 2. Results of bricks recycling for different number of recycling times

Table 3

	Difference with initial emergy seJ
Reuse	
1st	2.99E+11
2nd	3.89E+11
3rd	4.15E+11
4th	4.24E+11
5th	4.26E+11

Table 3. Results of new emergy of building for reuse of bricks (e.g. in concrete mix)