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Impact of building material recycle or reuse on selected emery ratios

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Abstract

While the emery evaluation method has been used successfully in recycling processes, this area of application still requires further development. One of such is developing emery 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 emery 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 emery evaluation of a low-energy building (LEB) in which a percentage of input materials are from recycled sources. The corresponding impacts on the emery yield ratio (EYR_B) and the environmental loading ratio (ELR_B) are studied. The EYR which is the total emery used up per unit of emery 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 emery 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 emery indices vary, even more, when greater amounts of material is recycled with higher amount of additional emery 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: Emery, 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 energy 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. Emery 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/C);
(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 emery based methodology to continuous matter reuse as devised by Amponsah et al. (2011) to a process. In fact, authors consider that the additional emery (coming from each recycle matter) can be aggregated to the “classical” emery evaluation which does not include any recycling. The different impacts this continuous reuse might have on the emery 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 emery 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 emery 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 emery required at each stage of recycle, impacts on the final output emery of the system usually increasing the output emery after each additional recycle.

As such, authors of the said paper pointed out that the specific emery 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 emery inputs $e_{mi}$ (emery of raw material, fuel, goods and services etc.) without recycle, and the specific additional emery needed for recycling (for reusing) $e_{mc}$. The sampling time for recycling is noted $T_e$.
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:

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

The specific emery of any matter at the $n^{th}$ recycling is the sum of three terms: the specific emery of raw material adjusted to its raw mass, the specific additional emery 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 emery inputs $e_{mi}$ and the specific additional emery needed for recycling $e_{mc}$ and the recycled part $q_m$ are independent of the discrete time, the specific emery of matter containing a recycled part can be easily calculated by underlying the sum of a geometric series, noted $\psi$:

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

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

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

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

Emery 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 emery yield ratio (EYR) is the emery of an output divided by the emery of those inputs to the process that are purchased from the economy;

- the emery investment ratio (EIR) is the purchased emery from the economy (services and other resources) divided by the free emery inflow from the environment.

- the environmental loading ratio (ELR) is the ratio of purchased and non-renewable indigenous emery to free environmental emery.
On this basis, Amponsah et al. (2011) extended these ratios to some dimensionless emery indices for a single recycled material. Assuming that the emery 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:

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

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

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

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

**Figure 1:** Emergy flows with additional emery for recycling

Emergy source is noted SE.

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

$$\Delta E_{mc}(q_m, n_m) = m_m e_{mc} q_m \left(\frac{q_m^n - 1}{q_m - 1}\right)$$  \quad (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 emery 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:
\[
EYR_p = \frac{E^0_P + \sum_{j=1}^{M} \Delta E_{jc}(q_j, n_j)}{E^0_{PF} + \sum_{j=1}^{M} \Delta E_{jF}(q_j, n_j)}
\]  

(10)

\[
EIR_p = \frac{E^0_{PF} + \sum_{j=1}^{M} \Delta E_{jF}(q_j, n_j)}{E^0_{PN} + E^0_{PR} + \sum_{j=1}^{M} \left( \Delta E_{j,F}(q_j, n_j) + \Delta E_{j,R}(q_j, n_j) \right)}
\]  

(11)

\[
ELR_p = \frac{E^0_{PF} + E^0_{PN} + \sum_{j=1}^{M} \left( \Delta E_{j,F}(q_j, n_j) + \Delta E_{j,N}(q_j, n_j) \right)}{E^0_{PR} + \sum_{j=1}^{M} \Delta E_{j,R}(q_j, n_j)}
\]  

(12)

Where \( E^0_P \) is the total energy of the process without any recycle matter. \( E^0_{PF} \), \( E^0_{PR} \) and \( E^0_{PN} \) are respectively its purchased, renewable and non renewable part. The additional energy of the \( j^{th} \) matter \( \Delta E_{jc} \) 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: \( e_{br} (100\%) = 3.68E+09 \text{ seJ/g} \), when reused \( e_{br} (100\%) = 2.6E+05 \text{ seJ/g} \) and when recycled \( e_{br} (100\%) = 4.8E+05 \text{ seJ/g} \), see Amponsah (2011, p158-160)
- steel via the electric arc furnace process: \( e_{st} (100\%) = 4.15E+09 \text{ seJ/g} \), \( e_{st} (100\%) = 9.0E+07 \text{ seJ/g} \), see Buranakarn (1998, p52)
- aluminium: \( e_{al} (100\%) = 1.27E+10 \text{ seJ/g} \), \( e_{al} (100\%) = 6.4E+08 \text{ seJ/g} \), see Buranakarn (1998, p60)
- plastic lumber: \( e_{pl} (100\%) = 5.75E+09 \text{ seJ/g} \), \( e_{pl} (100\%) = 5.8E+08 \text{ seJ/g} \), 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 m² 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/m² 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 emery part of whole building construction is considered as the sum of sun and water emery. Its purchased emery part is considered as the sum of fuel and electricity emery.

- In Table 1, the value of transformities corresponds to a process with no recycling. Without any recycled material, the total emery for building manufacturing, noted $E_B$, 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 emery 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 emery evaluation. The emery of the building is thus re-evaluated, taking into account different scenarios. As such, emery for sorting, collection and transportation to the recycling plant is considered, in addition to the emery for the plant process. This emery adds up to give the additional emery of bricks recycling ($\Delta E_{bc}$). For this building, the specific emery 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 emery 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 emery $\Delta E_{bc}(q_m, n_m)$, corresponds mainly to collection and separation, and is incorporated only in purchased inputs $\Delta E_{bc,F}(q_m, n_m)$. Equation (10) begins:

$$EYR_B = \frac{E^0_B + \Delta E_{bc,F}(q_b, n_b)}{E^0_{BF} + \Delta E_{bc,F}(q_b, n_b)}$$  \hspace{0.5cm} (13)

- The result for the first reuse ($q_b e_{bc}$) is added up to the initial emery of the building (ref. Table 1) 7.1E+16 seJ giving an emery 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 $EYR_{br}$ 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 $E_{br}^0$ 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 ‘resetting’ 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 $\text{EYR}_b$ of the building

Figure 4. Impact of different recycling rates for continuous bricks recycle (a) and reuse (b) on $\text{EYR}_b$ 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 $\text{EYR}_b$, see Fig. 5. Fig.6 shows the impact of recycled plastic on the emergy yield ratio ($\text{EYR}_b$) of the building.

Figure 5. Impact of 30% (constant rate) continuous plastic recycle on $\text{EYR}_b$ of the building

Figure 6. Impact of different recycling rates for continuous plastic recycle on $\text{EYR}_b$ of the building

As can be seen in the results of the $\text{EYR}_b$, ignoring the impact of material reuse or recycling leads to the loss of significant information. Extending the traditional $\text{EYR}_b$ 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 $\text{EYR}_b$. It is
observed that EYR8s are lower in higher recycling times. For instance, the difference between EYR8 for a 1st recycle and a 5th recycle is quite significant (3.92E+01). This is due to the significant changes in the additional energy amounts needed for the cycle of material recycling or reuse.

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

$$ELR_B = \frac{E_{BF}^0 + E_{BY}^0 + \Delta E_{bi,c} (q_b, n_b)}{E_{BR}^0}$$  \hspace{1cm} (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 recyle 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 emery as a purchased emery. If
one wants to allocate it to the product itself, by increasing its transormity in
emery table (as Table 1), then the additional emery is considered in the non
renewable part in the emery 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 emery 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
emery evaluation of a low energy building in France. The evaluation results reveal
significant impacts on the emery 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 $\psi$. In this way the difficulty of recalculation is somehow reduced, since the
factor could easily be selected depending on the time of recycling ($1^{st}$, $2^{nd}$, $3^{rd}$ 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...).

Acknowledgements

This paper has been developed from the results obtained within the framework of the EQUER project “Low Energy Consumption Buildings” by graduate students of the Ecole des Mines de Nantes. The study also has had financial support from Ecole des Mines de Nantes and Carnot M.I.N.E.S of France. Authors would like to thank the two anonymous reviewers for their helpful comments.

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Number of brick recycle (q_b=0.3)
Figure 6
Figure 7b

Energy Loading Ratio (ELRₜ) vs. Amount of reused brick (qᵣ):
- 1st Reuse
- 2nd Reuse
- 3rd Reuse
- 4th Reuse
- 5th Reuse
<table>
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<th>Note</th>
<th>Item</th>
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<th>Transformity (seJ/unit)</th>
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<td>4.80E+04</td>
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<td>kg</td>
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<td>d</td>
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<td>Unit</td>
<td>Transformity (seJ/unit)</td>
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<td>kg</td>
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<td>66</td>
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**Purchased Inputs**

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<th>Volume (m³)</th>
<th>Unit</th>
<th>Transformity (seJ/unit)</th>
<th>Ref.</th>
<th>Emergy (seJ)</th>
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<td>67</td>
<td>Nuclear (78%)</td>
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<td>J</td>
<td>2.00E+05</td>
<td>g</td>
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<td>68</td>
<td>Hydro (14%)</td>
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<td>70</td>
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<td>1.82E+09</td>
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</table>

Total emergy for building manufacturing

7.11E+16


Table 1. Emergy evaluation Table
Table 2. Results of bricks recycling for different number of recycling times

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<th>Recycling</th>
<th>( \Phi Ec, \text{J} )</th>
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<td>5.4E+11</td>
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<tr>
<td>2nd</td>
<td>7.1E+11</td>
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<tr>
<td>3rd</td>
<td>7.8E+11</td>
</tr>
<tr>
<td>4th</td>
<td>7.7E+11</td>
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<tr>
<td>5th</td>
<td>7.8E+11</td>
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<tr>
<td>Reuse</td>
<td>Difference with initial emergy seJ</td>
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<tr>
<td>-------</td>
<td>-----------------------------------</td>
</tr>
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<td>2.99E+11</td>
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<tr>
<td>2nd</td>
<td>3.89E+11</td>
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<tr>
<td>5th</td>
<td>4.26E+11</td>
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Table 3. Results of new emergy of building for reuse of bricks (e.g. in concrete mix)