Building and Environment 127 (2018) 187–203

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Towards more sustainable social housing projects: Recognizing the importance of using local resources

Biagio F. Giannetti[a,b,*], Jorge C.C. Demétrio[a,c], Feni Agostinho[a], Cecília M.V.B. Almeida[a], Gengyuan Liu[b]

[a] Paulista University (UNIP), Post-graduation Program in Production Engineering, Brazil
[b] School of Environment, Beijing Normal University, Beijing, China
[c] Maranhão State University, Brazil

A R T I C L E I N F O

Keywords:
Brazilian construction industry
Emergy
Social housing
Sustainable construction

A B S T R A C T

The social housing projects of Brazil are focused on providing shelter for families with low income and on reaching the ultimate objective of more sustainable development of the nation. The Brazilian program, in supporting these families, is carried out through three main standardized housing projects: popular housing (R1), popular building (PP4), and building for social interest (PIS). Decisions regarding the choice of one project instead of another are usually based on economic considerations, disregarding environmental issues important for achieving sustainable development. The main goal of this work is to assess which social housing projects should be promoted in each Brazilian state, aiming for higher sustainability. For this purpose, emergy accounting is used to quantify the environmental sustainability index (ESI*) and the emergy index for construction productivity (EICP, in m^2/sej). Results show the existence of different degrees of ESI* and EICP values among the three types of social housing projects, when considering the state in which projects are implemented. Analysis of the results identified the social housing projects that should be promoted to maximize ESI* and EICP aiming for higher sustainability. Choosing a project exclusively based on economic considerations could be premature, because it may forgo the opportunity to maximize sustainability of the national social housing program. This study also provides a scientific contribution to the emergy accounting method with regard to the scales of analysis that support the criteria used to count a resource as local or imported and in considering the partial renewabilities of resources according to regional characteristics.

1. Introduction

When the demand for energy & material resources and the damage of gas emissions are considered over a buildings life cycle [1], the building construction sector causes the highest environmental load on the Earth. Therefore, documenting and controlling load from the building sector is one key to achieving sustainable development. Some numbers provided by the United Nations Environment Programme (UNEP; www.unep.org) show that over their life cycle, buildings demand about 40% of total global energy use, 60% of global electricity, 25% of global water, 40% of all resources, and release about 1/3 of global greenhouse gases. However, the building sector that includes projects elaboration, materials suppliers and construction usually provides 5–10% of direct and indirect world employment and generates 5–15% of the GDP, on average. In this context, alternative new green construction methods and concepts may yield economic opportunities for developing countries; since in these countries, the building sector usually represents up to 40% of GDP. These numbers highlight the importance of reducing the usage of scarce resources and avoiding the harmful emissions from the construction sector, for the sake of both environmental and social well-being.

Agenda 21 for the Sustainable Construction Sector in Developing Countries was published after the Johannesburg World Summit on Sustainable Development in 2002. This document emphasizes the need for the development of efficient policies in the construction sector as a fundamental step towards sustainability, and it makes clear that developing countries have different needs when compared to developed countries [2]. In economic terms, Brazil can be considered an important developing economy with a growing construction sector expected to expand 100% between 2010 and 2022 [3]. On average, housing is responsible for about 26% of the total money circulating in the Brazilian construction sector, which is largely supported by real estate loans.

* Corresponding author. Universidade Paulista (UNIP), Programa de Pós-Graduação em Engenharia de Produção, Laboratório de Produção e Meio Ambiente, Rua Dr. Bacelar, 1212, CEP 04026–002, São Paulo, Brazil.
E-mail address: biafgian@unip.br (B.F. Giannetti).

https://doi.org/10.1016/j.buildenv.2017.10.033
Received 4 July 2017; Received in revised form 26 October 2017; Accepted 29 October 2017
Available online 31 October 2017
0360-1323/

Construction companies consumed about 30 billion USD in materials in 2014, and Brazilian families spent about 37% of their incomes on housing [4]. As a result, the construction sector was responsible for 4.3–7.0% of Brazilian GDP between 2000 and 2016 [5], which emphasize the importance of the construction sector for the Brazilian economy.

Six million is the estimated number of new dwellings needed to overcome the current housing deficit in Brazil [6]; such a large deficit primarily affects citizens with a monthly income lower than 500 USD. The demand for housing creates and supports new market possibilities for the construction sector, especially for the so-called "social housing" projects. The Brazilian Norm (NBR) 12,721/06 [7] promulgates the following three mostly subsidized social housing projects focusing on people with lower income: Popular Housing (R1), Popular Building (PP4), and Building for Social Interest (PIS). According to Brazilian law 11,124 of June 16th, 2005, the National System for Social Housing [8] aims to allow the poorest populations' access to urban lands, providing sustainable and worthy housing, promoting policies for economic subsidies related to the implementation of social housing projects, and supporting institutions that are directly connected to the social housing sector.

New construction demands resources for implementation and operation, which directly and indirectly cause environmental load, thus affecting regional, national, and global carrying capacities. The construction industry in Brazil has one outstanding characteristic: economic issues over a short time period are almost exclusively used to make decisions, while social and environmental issues are ignored in spite of the law (11,124). As identified by Sanfelice and Halbert [9], financial market conventions for housing in Brazil are not predetermined, but they vary over time, in response to observed financial results. Triana et al. [10] argue that currently housing policy in the country tends to prioritize capital costs, without considering long-term benefits, such as thermal performance. These authors found evidence of the need to improve thermal and energy performance of buildings in the social housing sector, and suggest that policies for the Brazilian social housing national program should consider impacts from a more holistic point of view. Accordingly, Paulsen and Sposto [3] found that half of the energy embodied during the life cycle of a building was due to the materials used for its maintenance, and around 25% was specifically directed to support the maintenance of building structure; the largest potential for improvement in reducing housing's embodied energy was related to the choice for wall materials with lower embodied energy and higher durability, so as to reduce the need for maintenance through materials substitution. Among others, several examples [11–13] can be found in the scientific literature explaining the use of alternative materials for building construction that have similar structural performance but with a higher degree of sustainability, e.g. the usage of available regional or local resources with higher durability, lower embodied energy, and lower emissions in their production chains.

Evaluating the environmental impacts caused by implementing social housing, Scheidt et al. [14] emphasize the lack of holistic and clearly presented criteria, and suggest a multidisciplinary approach for developing more objective criteria for making decisions. For the Brazilian case, these authors argue that the inadequacy in implementing projects could result in a series of increased environmental loads. Yi et al. [15] emphasize the necessity to integrate energy and environmental impacts under a higher scope of analysis to achieve global sustainability in a building as part of the whole built environment. Srinivasan et al. [16] state the importance of including methods that also quantify the impact of energy being used by ecosystems that indirectly contribute to building life cycle energy use. According to these authors, this approach will support better sustainability-related decision making in the design, construction, operation, and decommissioning of buildings. Pulselli et al. [17] have found evidence of climatic and regional influences on the energy performance of building envelopes. Thus, the social housing projects should consider a holistic perspective (including environmental factors) rather than exclusively focusing on the needs of final users. Besides considering the demand for energy, material resources, and the outputs generated during the usage phase of social housing, it is essential to know the origin of each resource used during the implementation phase in other to understand the interaction between the productive systems and their surrounding environment. Scipioni et al. [18] also highlights the need for more appropriate models of construction that consider the regional or local carrying capacity.

The number of registered Leadership in Energy and Environmental Design (LEED) projects in Brazil is the fourth largest in the world [19]. Many locally adapted certification tools have been developed and are increasingly becoming more popular and successful throughout the country. For example, AQUA, Selo Azul da CAIXA, Qualiverde certification, and GBC Brazil are locally adapted certifications of "green" buildings for the commercial, residential and social housing sectors. Although these certification tools make a positive contribution towards increasing the quality of construction from an engineering/building perspective, all these tools disregard the important criterion of the origin of materials and energy, which strongly affects the sustainability of housing projects. This issue could be overcome by recognizing the importance of the scale under analysis, when choosing the most appropriate social housing projects to move towards more sustainable development in Brazil. The idea is that, instead of choosing unique projects based exclusively on economic issues, biophysical indicators should also be considered in deciding which social housing projects are most appropriate for each Brazilian region. In this sense, the following questions arise: "Are there differences in performance among the types of social housing projects R1, PP4, and PIS with regard to their sustainability, when implemented in the various Brazilian states?", and "What type(s) of social housing projects should be established in each Brazilian state so that it will move towards higher sustainability?

In addition to proposing solutions for the implementation of social housing based on theoretical assumptions, it is important to quantify them, in order to assess their relationship to increasing sustainability. For this purpose, emergy accounting [20], among other scientific methods available in literature, can be considered as a powerful alternative valuation method to economics due to its strong scientific and thermodynamic basis and the body of work in this field that has been used to answer questions and address issues regarding sustainability [21,22]. Emergy accounting is concerned with the demand for resources originating from a production system (i.e. taking an upstream view). The method considers both natural and economic resources under a holistic perspective; it has been described as a robust method [23], since it recognizes the quality of energy in the analysis and provides a series of indicators that support a discussion on sustainability. Emergy accounting has been applied under different approaches to access energy efficiency and sustainability in the building sector [15–17,24,25], but the goals and the methodological approach used in these studies differs, in part, from the method as used in this study.

This work assesses social housing projects (R1, PP4, and PIS) to determine which one is the most appropriate to be implemented in each one of the 27 Brazilian states (26 states and 1 Federal District) envisioning higher environmental sustainability as a goal. This study could be considered by decision-makers as a method to consider environmental sustainability in the design and implementation of social housing projects, and to highlight the importance of considering biophysical indicators in making a decision rather than exclusively economic ones.

More than the use of the emergy method in a case study, this work also presents, uses and discusses alternative interpretations of sustainability indicators from the emergy accounting method. The idea is to contribute to further discussions in the scientific community on this important issue. In short, this work considers: (a) The exchanges of resources among the Brazilian states, so the criteria used to classify resources as renewable, nonrenewable and/or imported depends on the existence of a storage for that resource within the state; (b) The partial renewabilities in the emergy calculation procedures, mainly for electricity, wood, and the labor force. The argument is that any resource could have a partial renewability, even if it comes from the larger economy that usually depends on fossil fuel. Both procedures could result in more precise values for the environmental sustainability index (ESI), especially important in countries with large and complex territories such as Brazil (8.5 million km^2 including 27 states with different social, economic and environmental characteristics) since these differences could influence the results of sustainability assessments.

2. Methods

2.1. Characterization of the social housing and data sources

In 1964, the Brazilian government established law no. 4591/64 that emphasizes the need to know the monetary costs related to building construction. As a result of this law, all syndicates of the building sector for the 27 Brazilian states must publish a monthly report containing the named Basic Unitary Cost (CUB; Portuguese acronym). The CUB indicates the market value of a square meter built for different building projects. This law allowed the creation of the subsequent law no. 12,721/2006 that provides definitions and characteristics for 21 standardized building projects that, in principle, should receive economic support from the government. The 21 building projects described in the law encompass the so-called high, medium and low building engineering characteristics, which depend on the monetary resources available for construction. They differ in size and in the quality of the products used for finishing. For social reasons, until 2015 the Brazilian government had invested about 75 billion USD in housing projects to meet the needs of low-income citizens. Among them, the following three types of projects are being strongly supported:

(a) Popular housing (R1) measuring 58.64 m^2, featuring two bedrooms, living room, bathroom, kitchen, and laundry room;
(b) Popular building (PP4) measuring 1415 m^2, featuring a ground floor (353.75 m^2) and three other floors containing four apartments, each 88.44 m^2, and containing two bedrooms, living room, bathroom, kitchen, and laundry room;
(c) Building of social interest (PIS) measuring 991.45 m^2, featuring a ground floor (198.29 m^2) and four other floors containing four apartments, each 49.57 m^2, and including two bedrooms, living room, bathroom, kitchen, and laundry room.

Recognizing that the money used to support these social housing projects comes from the public treasury, it is important to identify the most economical social housing projects to guarantee the efficient use of public resources. However, when considering sustainability, the efficient use of public resources must be viewed under a biophysical perspective and this viewpoint is important for supplying scientific-based information on the environmental subsidies required by decision makers. The three social housing projects (R1, PP4, and PIS) are evaluated in this study using a biophysical perspective. Raw data are obtained from two sources: Brazilian law no. 12,721/2006 and from different CUBs published by the syndicates of building sector in Brazil (see Table A.1, Appendix A).

2.2. Assessing sustainability under the emergy approach

Several methods providing indices capable of supporting a discussion on sustainability are found in the scientific literature. As stated by Agostinho and Pereira [26], all methods can be considered useful to some extent, but they support different discussions, since different scales of analysis and dimensions are considered in their frameworks; i.e., different concepts and definitions about the meaning of sustainability are considered, resulting in different conceptual models.

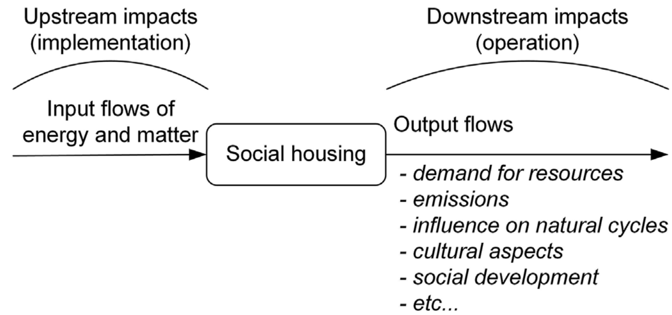

Fig. 1. Social housing as an open system as shown by the conceptual model of sustainability used in this work. Social development could include security, health care, education, and so on.

Research on the building sector mainly relates to energy and thermal efficiencies, alternative materials, CO_2 emission, water recycling, as well as economic and social aspects [10,11,27–29]. All these studies discuss ways to make for the operational phase of building usage more sustainable, i.e. the building usage by people, or the so-called downstream impacts (Fig. 1). On the other hand, in the implementation phase the upstream impacts should also be considered relevant due to the paramount usage of materials and energy by the global building sector that causes environmental load [3,30–32]. In this case, emergy accounting appears to be an appropriate alternative method to quantify sustainability, mainly because it considers all resources from nature and from the economy in its framework by covering both upstream and downstream impacts.

Emergy is defined as “the available energy of one kind of previously used up directly and indirectly to make a service or product” [20]. In essence, emergy accounting focuses on a donor side perspective (Fig. 2), taking into account all resources from nature and from a larger economy required by the transformation system to provide a service or a product. The market value of a good or service is usually defined by the willingness to pay. Value relative to willingness to pay can be estimated exclusively by considering a receiver side perspective according to current needs and expected benefits in acquiring a good or service, so it is a subjective approach that can go up and down according to the good's/service's scarcity or abundance. As stated by Odum [20], market prices do not add any important information when evaluating the contribution from the environment for a production system, and, in fact, go in an opposite direction, i.e. market prices are low when environmental contributions to a productive system are high and vice versa. Odum [20] also argues that real wealth is based on a donor side perspective, exemplified by Campbell et al. [33] as what a quantity of available energy, material or information can do when used in a system for its intended purpose as contrasted with its monetary value (e.g. a given car will drive only so far on a liter of gas, regardless of the price paid at the pump).

Besides the donor side perspective, a second aspect also important in the emergy method is energy quality; deeper discussions can be

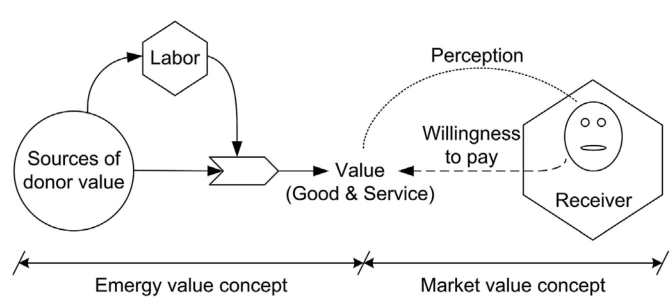

Fig. 2. Emergy and market concepts of value. Adapted from Odum [20].

found in Odum [20], but some key ideas are summarized here. Everything on the Earth can be considered as connected by means of energy flows, and there is a hierarchy of energy transformation processes such as the well known trophic chain; solar radiation supports grass growing that supports insects and other small animals and so on, until the energy reaches the end of the chain, where lions and other top carnivores are found. From the left to right side in the hierarchy, a huge amount of dispersed energy (solar radiation) supports a lower amount of less dispersed energy (grass), and so on, until it reaches a highly concentrated form of energy represented by the lions, which is a new form of energy in smaller overall quantity, but with a larger area of influence. According to the 2nd law of thermodynamics, available energy is lost during all transformation processes and the available energy is reduced for the subsequent stage in the chain. This implies that the quality of energy is different for each stage, so 1 J of solar radiation has lower quality than 1 J of lions. Another simple example is that 1 J of fossil fuel is not able to provide the same kind of work as 1 J of electricity, although both are measured by Joules. The idea is that to generate 1 J of electricity more than 1 J of fossil fuel is needed (to construct a power plant, machines, and also in converting fossil fuel directly into electricity in turbines). Energy quality is an important concept used in emergy accounting and it is represented by the Unit Emergy Value (UEV), obtained by dividing all input emergy demanded by the system by its output. Specifically for this work, the inverse of UEV can be viewed as an emergy index of construction productivity (EICP) relating output to input, i.e. EICP = 1/UEV.

Although seemingly conceptually complex, emergy is an accounting method usually performed in three simple steps:

(a) Modeling the system under study by considering the Energy Systems Language as suggested by Odum [20,34]. The energy systems diagram is, in fact, a conceptual representative model of the real system under study, in which the main external and internal flows of energy, material, labor and information are connected with the internal components and processes that allow the system to function, generating one or more outputs. Fig. 3 shows a basic energy diagram to represent the main drives supporting the system. Usually, the basic energy diagram has three main components including energy sources from renewable resources (R), from nonrenewable resources (N), and resource feedback from the larger economy (F) that support the system and generates outputs. Different from the classical variables used in emergy accounting, this work considers all resources coming from the outside state boundaries as Imported (Im) instead of feedback from the economy (F) that includes energy, material and services. Services are not considered as an energy flowing into the system, because they are strongly influenced by the existing subjectivities of the traditional economic market (cost of opportunity, willingness to pay, offer and demand, and so on). This work highlights the system's dependence on external resources, so material & energy resources coming from the same state in which the social housing projects are built are classified as "N" or "R" depending on their renewability fraction. The boundaries of Fig. 3 represent each one of the 27 Brazilian states, and the internal rectangle (box symbol) represents the social housing projects.

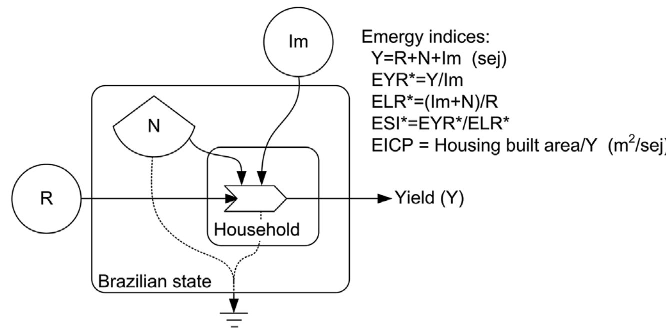

Fig. 3. Aggregated energy systems diagram and emergy indices. Symbols from Odum [20]. R: natural renewable resources; N: local (within state) nonrenewable resources; Im: imported (outside state) materials and energy resources from a larger economy; Y: total emergy demanded by system; EYR*: modified emergy yield ratio; ELR*: modified environmental loading ratio; ESI*: modified environmental sustainability index EICP: emergy index of construction productivity.

(b) The second step is to obtain the emergy table by quantifying all the previously identified flows of available energy (J), materials (g), labor force (hours) and money flow (USD), and then convert all these flows into emergy units by using appropriate UEVs in sej/J, sej/g, sej/h, and sej/USD, respectively. Currently, with the increase of emergy accounting analyses and publications, the UEVs for different processes, materials, fuels, etc., can be found in databases and in the scientific literature. This conversion process accomplished by using published UEVs, besides considering the energy quality concept as explained before, results in different flows being expressed in the same unit, solar emjoules (sej). Although services input flows are disregarded in this work, the labor & services embodied (or indirect services) in the UEVs are considered; please see Ulgiati and Brown [35] in this regard. Additionally, all the UEVs are referenced to the emergy baseline of 15.83E24 sej/yr [36]. For a best practice, the established baseline of 12.0E24 sej/yr [37] should be used in future emergy studies, however, considering that a comparison among systems are realized here, the resulting difference would be the same, independently of the emergy baseline being used. Details on a historical review of emergy baseline calculation can be found on Campbell [38].

(c) Finally, after converting all systems energy drivers into the same unit (sej), the emergy indices can be calculated to support discussion about the emergy performance of the evaluated systems. Fig. 3 shows the most traditional and often used emergy indices, each one with different algebra and importance in indicating different aspects of the system under study. The superscript symbol * is used in this work to highlight that traditional emergy indices algebra and meanings are, to some extent, different from those used in this work. This is a result of considering imports "Im" and local non-renewable resources "N" differently than traditional approaches as found in the emergy literature; "Im" as materials and energy imported from other states, and "N" representing local natural non-renewable resources added to resources from the economy originated within the state. The EICP and ESI* are used in this work to support discussions about the emergy performance of evaluated social housing projects.

The EICP is an emergy index that indicates system productivity on a global scale by relating outputs with inputs. If the aim is to produce more outputs by consuming lower amounts of global resources (mainly low amounts of the nonrenewable ones), systems with higher EICPs making equivalent products are the most efficient ones. In this work, the EICPs of the social housing projects relate the demand for global resources in implementing these projects with area of building constructed, thus the social housing project having higher EICP value in m^2/sej of housing built can be considered the most efficient project and should be supported. However, the most efficient project sometimes may not be the most sustainable one, since resource inputs can originate from nonrenewable sources. Thus, the ESI* emergy index is also used to complement these discussions. ESI* is a relation between emergy yield and environmental load (Fig. 3), and considering that higher emergy yield and lower environmental load are the targets, then higher values for ESI* indicate higher environmental sustainability. The main goal of the assessment is to choose the social housing projects that depend mostly on renewable resources and have higher productivity in converting these resources to shelter. In other words, projects with higher emergy index of construction productivity "EICP" quantified in terms of the area of housing built per sej of resources used (m^2/sej and higher ESI*, which are those that are most sustainable. This same approach has been used before by Bonilla et al. [39] and Almeida et al. [40].

2.3. Approach for the analysis of results

Two graphical approaches are considered to support discussion of the results: (a) the emergy ternary diagram, and (b) a graph representing the environmental sustainability index (ESI*) in relation to the emergy index of construction productivity (EICP) in m^2/sej.

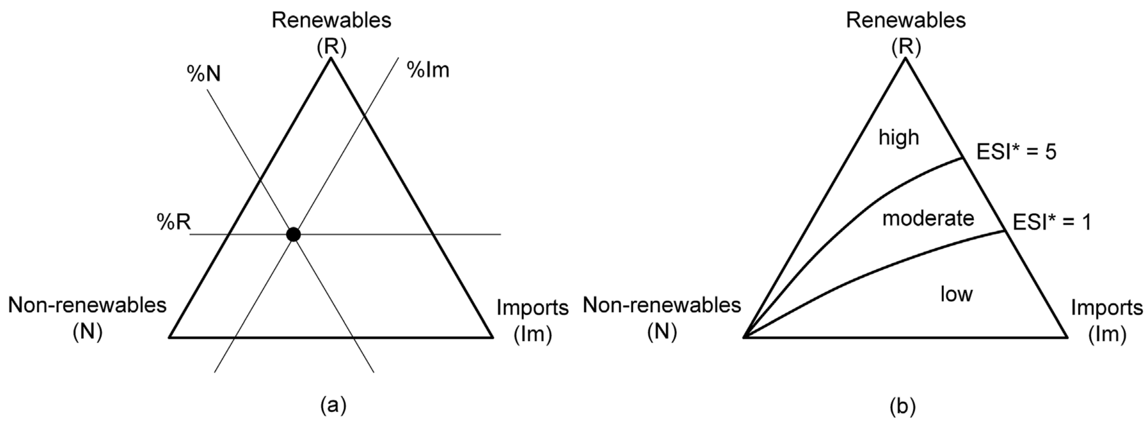

Fig. 4. Ternary diagram used to represent emergy performance: (a) a generic point representing a production system with a specific proportion for R, N and Im emergy inflows; (b) ternary diagram representing the three regions of sustainability according to the emergy accounting method. ESI* = Environmental Sustainability Index.

The emergy ternary diagram has three components according to the categories of aggregated emergy flows, including renewables (R), nonrenewables (N) and imports (Im). These three components are represented in an equilateral triangle. Each internal point in the triangle represents a production system that demands a certain amount of emergy with a certain proportion of R, N, and Im resources. Fig. 4a shows an example of a ternary diagram containing an arbitrary point for better comprehension. Additionally, the diagram was used to visualize and understand the ESI* for an individual or even a group of production systems graphed together; simple comparisons can be drawn, as well as tendency or temporal studies (see for instance, Giannetti et al. [41]). The sustainability lines, which represent constant values of ESI*, depart from the N vertex in the direction of R-Im side creating sustainability areas (Fig. 4b). The following meaning of the traditional ESI values as proposed by Brown and Ulgiati [42] is used in this work to represent the ESI* as well: ESI* < 1 indicates low sustainability; 1 < ESI* < 5 indicates moderate sustainability; ESI* > 5 indicates high sustainability. According to Giannetti et al. [43], adopting emergy-based ternary diagrams provides a better understanding of the actual contribution of a given set of inputs and a better representation of the global sustainability of production processes. These authors suggest that the emergy ternary diagram allows a transparent representation of the results and may serve as an interface between emergy scientists and decision makers; some authors [44] suggest that the use of emergy ternary diagrams corresponds to a fourth step in emergy synthesis. Deeper analysis of the emergy ternary diagram can be also found in Almeida et al. [45].

Combining outcomes with high ESI* and high EICP values provides a more comprehensive set of information to guide decision makers towards more sustainable solutions with lower resource use. Placing the ESI* and EICP in the same graphic seemed interesting, since the area within the lines would represent a measure of the “goodness of fit” of the systems from a sustainability point of view [39]. After calculating the EICP for each social housing project for all Brazilian states, results are graphed against the previously obtained ESI* indices. The interpretation of Fig. 5 can be considered as follows: region (a) indicates low environmental sustainability and productivity (i.e. high environmental costs for lower shelter gains); region (b) indicates high sustainability but low productivity of shelter construction; region (c) is representative of high sustainability and and high productivity in converting resources to shelter; and finally (d) indicates low sustainability but high productivity in the construction of shelter. This graph is used to show the most promising social housing projects, which are those with both higher productivity and higher environmental sustainability; this can be easily seen in the graph by considering the highest areas obtained combining EICP and ESI* for each social housing project (see dot (1) in Fig. 5 as an example). The lines establishing the region boundaries on

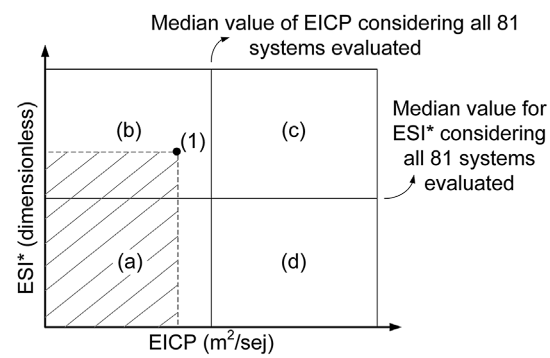

Fig. 5. Environmental sustainability (ESI*) versus emergy index of construction productivity (EICP) graph. Internal regions are (a) low ESI* and EICP, (b) high ESI* and low EICP, (c) high ESI* and EICP, and (d) low ESI* and high EICP. The interpretation of dot (1) is within the main text.

the graph are calculated by considering the median values of ESI* and EICP of all 81 systems evaluated (27 states by 3 social housing projects). This is justified by the fact that, rather than a comparison with other similar systems around the world, this research aims to provide a scientific-based method to choose the social housing project for each state according to the highest emergy performance.

3. Results and discussions

Fig. 6 shows the energy systems language diagram representing the housing projects as a representative model of the real systems studied. All flows of energy, materials, labor, indirect services and other drivers are displayed in the diagram using symbols and meanings from the Energy Systems Language [20,34]. The outer rectangle indicates the boundaries of each of the 27 Brazilian states, whereas the internal rectangles indicate the boundaries of the three types of social housing projects evaluated: popular housing (R1), popular building (PP4), and building for social interest (PIS).

The diagram shows that all social housing projects demand resources such as materials, energy and labor, and generate mainly solid waste that is disposed of in landfills. The resources used to build the social housing projects do not usually come from the same state in which they are being built, so imports of resources from other states is common. Fig. 6 shows other important aspects such as the flows of money represented by the dashed lines, always moving in countercurrent to energy flows. Money is used to pay for labor and services, but never to pay for nature's work required for the natural resources used. In the diagram, the government acts as a source of economic subsides to allow the social housing projects to be carried out, as these projects are directed to help people with lower income (i.e., it is a government

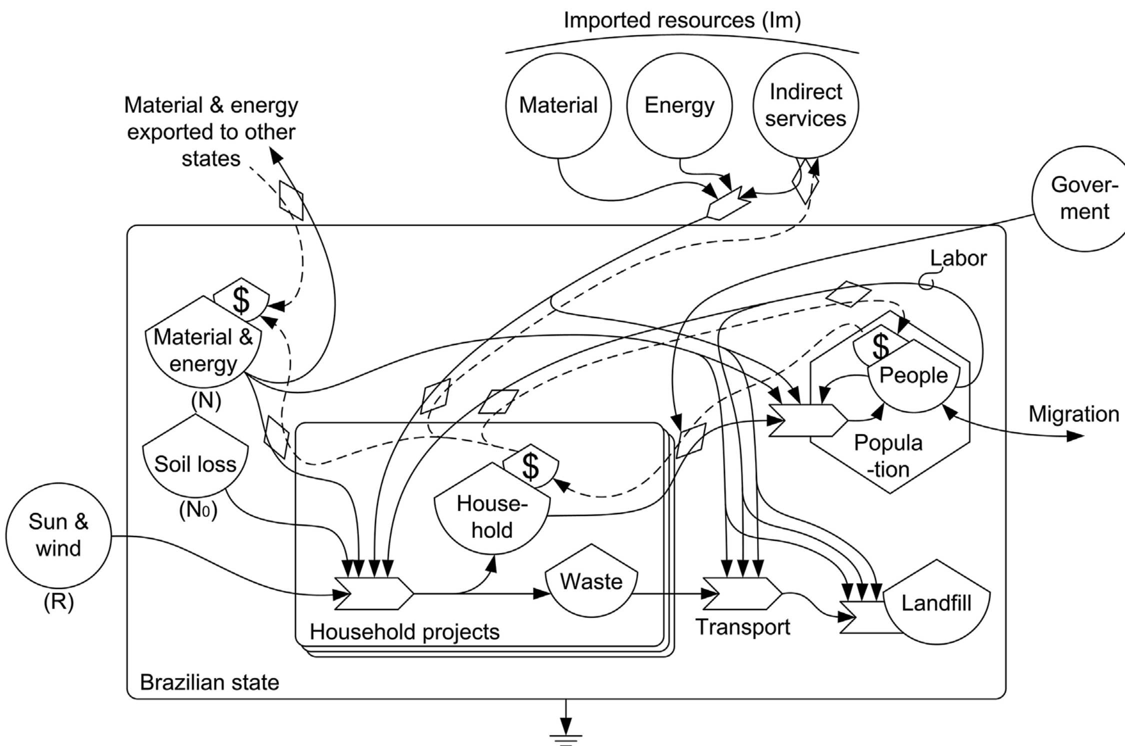

Fig. 6. Energy diagram representing the social housing projects evaluated. Energy Systems Language symbols from Odum [20,34]. Legend: R: renewable resources; N: nonrenewable resources; Im: imported resources from the larger economy of other Brazilian states.

priority to increase social welfare). Finally, the labor used during the implementation phase of social housing projects can come from inside the state, or from other states depending on the availability of skilled workers.

Once an understanding of the systems under study has been attained by visualizing their functioning with the energy systems diagram focused mainly on the demand for local or external resources, the emergy accounting method can be applied to quantify those resources and obtain emergy indicators of productivity and environmental sustainability.

3.1. Emergy global productivity for the social housing projects evaluated

Tables 1–3show the emergy accounting data for the three social housing projects being constructed in Brazil, using average values from the national scale, and disregarding for now, the origin of these resources and the necessary transportation processes. Tables have the same structure to facilitate comparisons, which does not mean that all systems have the same kind and amount of energy inputs.

The tables account for the construction phase of the social housing projects including the need for energy, materials and labor. The discharge of residues to landfills is also considered by accounting for the transport of residues and the landfill itself. Individually, popular housing projects (R1) are strongly dependent on the emergy from brick (22% of total emergy demanded), followed by sand 15%, labor 12%, with granite, steel, cement and wallboard contributing around 8% each. For the popular building project (PP4) similar results were obtained: brick 18%, labor 15%, sand 14%, cement 12%, steel and granite 10%. The building for social interest projects (PIS) also show results similar to PP4, except for labor that reached 12% of the total emergy demand. It is interesting to note that, although possessing different structural characteristics, the emergy signatures of all three types of social housing projects evaluated are similar.

The total emergy demanded by each social housing project indicates that the R1 project demands lower amount of solar emjoules resources per m^2 of building constructed (6.23 E15 sej/m^2) than PIS (7.93 E15 sej/m^2) and PP4 (8.25 E15 sej/m^2), indicating that R1 demands a lower amount of global resources per square meter built. In a world with reduced availability of resources, the most efficient process of any kind should be promoted and, in this case, the R1 project should receive priority over PIS and PP4. It is important to highlight that although R1 demands a lower amount of global resources per square meter built, this social housing demands a larger area to shelter the same amount of people than the two others housing projects, which may be a limiting factor for its implementation in some regions with restricted geographical land area. For comparison, Pulselli et al. [32] provide a value of 1.07 E19 sej demanded for a mixed building (housing and offices) in Italy with 2700 m^2, resulting in 3.96 E15 sej/m^2; Carvalho [46] obtained a value of 5.43 E15 sej/m^2 evaluating popular housing buildings in Brazil; Rothrock [30] found an emergy demand of 4.24 E15 sej/m^2 by a so-called sustainable residence with 176 m^2 built using alternative materials; Srinivasan et al. [16] obtained a value of 3.67 E15 sej/m^2 for the construction phase of Rinker Hall at University of Florida USA; Reza et al. [47] obtained values of 4.14 E15 sej/m^2 for multi-unit residential and 1.96 E15 se/m^2 for single-family house in Vancouver, Canada (including the construction phase, labor, engineering and management); Yi et al. [48] obtained 2.62 E15 sej/m^2 for the building envelope of a net-zero energy building in South Korea; Yi et al. [15] found a value of 0.39 E15 sej/m^2 for a med-size office building in USA; Yi and Braham [24] obtained 7.44 E15 sej/m2 (340.73 m^2; envelope life of 58 yrs) for a typical single-family house in Pennsylvania, USA; and Pulselli et al. [17] found values of 0.56, 0.62, and 0.71 E15 sej/m^2 for building envelopes in Italy according to technology and general climate conditions. All these referenced values range from 0.39 to 7.44 E15 sej/m^2; numbers were converted to the same emergy baseline of 15.83E24 sej/yr, except for [15] and [17] who did not mention the emergy baseline considered in their work.

Albeit important, the above results represent average values for the social housing projects in Brazil, a country that has an area of about 8.5 million km^2, 200 million inhabitants, 6 natural biomes, and different

Table 1
Emergy table for the popular housing (R1) project under a Brazilian national context.

Item[a]	Description	Amount	Unit/m^2	UEV[b] (sej/unit)	Emergy in sej/m^2	Emergy in %
1	Solar radiation	1.39E+05	J	1.00E+00	1.39E+05	< 0.1
2	Wind	1.23E+05	J	2.45E+03	3.01E+08	< 0.1
3	Wood (renew.)	5.92E+00	kg	2.40E+12	1.42E+13	0.2
4	Electricity (renew.)	1.28E+09	J	1.47E+05	1.88E+14	3.0
5	Labor (renew.)	1.53E+01	J	1.77E+13	2.71E+14	4.3
6	Soil loss	1.44E-03	J	1.24E+05	1.79E+02	< 0.1
7	Electricity (non-renew.)	1.19E+09	J	1.47E+05	1.75E+14	2.8
8	Wood (non-renew.)	4.28E+00	kg	2.40E+12	1.03E+13	0.2
9	Steel	7.02E+01	kg	7.81E+12	5.48E+14	8.8
10	Copper	3.47E-01	kg	1.04E+14	3.61E+13	0.6
11	Sand	5.78E+02	kg	1.68E+12	9.71E+14	15.6
12	Brick	3.81E+02	kg	3.68E+12	1.40E+15	22.5
13	Wares	5.66E+01	kg	4.80E+12	2.72E+14	4.4
14	Cement	1.73E+02	kg	3.04E+12	5.26E+14	8.4
15	Glass	1.37E+00	kg	1.41E+12	1.93E+12	< 0.1
16	Wallboard	1.34E+02	kg	3.29E+12	4.41E+14	7.1
17	Granite	2.33E+02	kg	2.44E+12	5.69E+14	9.1
18	Asphalt	1.23E+00	kg	2.55E+13	3.14E+13	0.5
19	PVC plastic	4.48E-02	kg	9.86E+12	4.42E+11	< 0.1
20	Paint (ink)	3.24E+00	kg	2.55E+13	8.26E+13	1.3
21	Water	6.80E+02	kg	3.27E+08	2.22E+11	< 0.1
22	Labor (non-renew.)	2.27E+01	h	1.77E+13	4.02E+14	6.5
23	Trucks for transportation	4.00E-01	km	9.42E+10	3.77E+10	< 0.1
24	Diesel	6.20E+08	J	1.81E+05	1.12E+14	1.8
25	Labor (renew.)	1.35E-01	h	1.77E+13	2.39E+12	< 0.1
26	Labor (non-renew.)	2.02E-01	h	1.77E+13	3.58E+12	0.1
27	Landfill	2.98E+02	kg	1.97E+10	5.87E+12	0.1
28	Diesel	6.20E+08	J	1.81E+05	1.12E+14	1.8
29	Trucks for transportation	4.00E-01	km	9.42E+10	3.77E+10	< 0.1
30	Labor (renew.)	1.06E+00	h	1.77E+13	1.88E+13	0.3
31	Labor (non-renew.)	1.75E+00	h	1.77E+13	3.10E+13	0.5
Total emergy for the popular housing project (R1):					6.23E+15	100.0

[a] Calculation details at Appendix A.
[b] UEVs at Appendix B.

development patterns for each one of its 27 states. Every state has a different basic unitary cost for construction, specific demand for transport depending on the origin of the imported resource, and differences in the UEV of the labor force due to each state's emergy characteristics and number of inhabitants. Thus, different performance for the same social housing project is expected when taking into account the need for transportation and the characteristics of the regional labor force, because they have a significant influence on the final emergy demand. To determine whether there are differences in emergy required per m^2 built for the three evaluated types of social housing projects according to the state in which they are located, 81 new emergy tables – comprising three types of social housing in 27 states – were performed and the results are presented in Fig. 7.

Further analysis of building construction in Brazil can be performed by considering the numbers provided in the Supplementary Material, where each of the 81 cases examined along with their emergy accounting tables are given. But rather than verifying what input flow has higher or lower influence on the total emergy required for each social housing project in a state, a most important discussion, to reach the main goals of this work we focus on determining the social housing projects with lower emergy demand and the reasons for their preeminence. For instance, Fig. 7 shows that the popular housing project (R1) demands lower amount of emergy (in sej/m^2) for the PB State, the popular building project (PP4) in the RO State, and the building for social interest (PIS) in almost all Brazilian states (best performance for the PB State). This result implies that the characteristics of each state have an influence on the availability and renewability of resources and consequently on the emergy required for the social housing projects. This can be visualized by comparing the emergy per m^2 built of social housing projects determined under the context of Brazilian average conditions (Tables 1–3) with the results in Fig. 7; for the former, the R1 project can be considered as the most efficient, but when accounting for the specificities of each Brazilian state, Fig. 7 shows that PIS is the most efficient housing project followed by R1 and PP4. Another important aspect is that PIS has the lowest demand for emergy for all 27 Brazilian states, suggesting that PIS social housing projects should be promoted instead of R1 and PP4 under an emergy efficiency perspective; especially when compared to PP4 that had the worst performance in all 27 Brazilian states.

These results indicate that there are differences regarding the emergy demanded for the three types of social housing projects and that these differences should be considered by managers when basing decisions on sustainability issues. Usually, decisions on what social project should be established in each state are based on economic (and sometimes political) issues, disregarding other important variables that would move towards more sustainable development. Although recognizing that there are other important issues that should be considered in making a decision (such as cultural, social, climatic, landscape, and so on), Fig. 7 indicates that proposing a PP4 social housing project for any state will result in lower performance in converting global resources into housing, and this goes against strategic planning to move towards sustainability.

As presented earlier, emergy per m^2 built is an important index, but it does not reveal anything about the origin or degree of renewability of the resources used, which is considered to be important information in assessing sustainability. To complement the discussion on what social housing project is more aligned to the sustainability concepts, the environmental sustainability index is also calculated and discussed in the next subsection.

3.2. Environmental sustainability performance for the social housing projects evaluated

A single graph containing the 81 values of the environmental

Table 2
Emergy table for the popular building (PP4) project under a Brazilian national context.

Item[a]	Description	Amount	Unit/m^2	UEV[b] (sej/unit)	Emergy in sej/m^2	Emergy in %
1	Solar radiation	1.14E+05	J	1.00E+00	1.14E+05	< 0.1
2	Wind	1.02E+05	J	2.45E+03	2.50E+08	< 0.1
3	Wood (renew.)	6.11E+00	kg	2.40E+12	1.47E+13	0.2
4	Electricity (renew.)	1.28E+09	J	1.47E+05	1.88E+14	2.3
5	Labor (renew.)	1.29E+01	h	1.77E+13	2.28E+14	2.8
6	Soil loss	1.44E-03	J	1.24E+05	1.79E+02	< 0.1
7	Electricity (non-renew.)	1.19E+09	J	1.47E+05	1.75E+14	2.1
8	Wood (non-renew.)	4.42E+00	kg	2.40E+12	1.06E+13	0.1
9	Steel	1.06E+02	kg	7.81E+12	8.28E+14	10.0
10	Copper	8.17E-01	kg	1.04E+14	8.50E+13	1.0
11	Sand	6.87E+02	kg	1.68E+12	1.15E+15	14.0
12	Brick	3.95E+02	kg	3.68E+12	1.45E+15	17.6
13	Wares	5.59E+01	kg	4.80E+12	2.68E+14	3.3
14	Cement	3.38E+02	kg	3.04E+12	1.03E+15	12.5
15	Glass	1.90E+00	kg	1.41E+12	2.68E+12	< 0.1
16	Wallboard	1.37E+02	kg	3.29E+12	4.51E+14	5.5
17	Granite	3.30E+02	kg	2.44E+12	8.05E+14	9.8
18	Asphalt	1.78E+00	kg	2.55E+13	4.54E+13	0.6
19	PVC plastic	1.47E+01	kg	9.86E+12	1.45E+14	1.8
20	Paint (ink)	3.91E+00	kg	2.55E+13	9.97E+13	1.2
21	Water	6.80E+02	kg	3.27E+08	2.22E+11	< 0.1
22	Labor (non-renew.)	1.92E+01	h	1.77E+13	3.40E+14	4.1
23	Trucks for transportation	4.00E-01	km	9.42E+10	3.77E+10	< 0.1
24	Diesel	6.20E+08	J	1.81E+05	1.12E+14	1.4
25	Labor (renew.)	5.14E-03	h	1.77E+13	9.10E+10	< 0.1
26	Labor (non-renew.)	7.66E-03	h	1.77E+13	1.36E+11	< 0.1
27	Landfill	3.20E+02	kg	1.97E+10	6.30E+12	0.1
28	Diesel	6.20E+08	J	1.81E+05	1.12E+14	1.4
29	Trucks for transportation	4.00E-01	km	9.42E+10	3.77E+10	< 0.1
30	Labor (renew.)	1.58E+01	h	1.77E+13	2.80E+14	3.4
31	Labor (non-renew.)	2.35E+01	h	1.77E+13	4.16E+14	5.0
Total emergy for the popular building (PP4):					8.25E+15	100.0

[a] Calculation details at Appendix A.
[b] UEVs at Appendix B.

sustainability index (ESI*) for the three types of social housing projects in the 27 Brazilian states could make the results of this comparison difficult to interpret. For this reason, three ternary diagrams were used for this analysis and they are shown in Figs. 8–10, where each figure is related to a type of social housing (R1, PP4 and PIS). The Supplementary Material addendum to this paper contains all numbers, tables and results discussed here. For the R1 project, Fig. 8 shows that states such as Amapá (3), Amazonas (4), Roraima (23), Maranhão (10), Mato Grosso (11), Pará (14) and Minas Gerais (13) were the only ones that obtained an ESI* higher than 1, indicating moderate sustainability; no state obtained an ESI* higher than 5. Most of these quoted states (3, 4, 23, 10 and 14) with an ESI* higher than 1 are located close to the Amazon biome, a region that still has high availability of natural renewable resources which has an influence on the renewability fraction (from 76 to 98%; see Appendix C) of labor and wood, used in these provinces. Additionally, resources such as wood, cement and wallboard are regionally available (see Appendix C), which makes the transportation of resources from other states unnecessary, thereby increasing sustainability due to reduction in the demand for diesel fuel. This could be a plausible explanation for the higher values of ESI* in these provinces. Other states are also located close to the Amazon biome (e.g. Acre #1, and Rondônia #22), but they do not produce enough quantity or kinds of all needed resources for the building sector (maybe due to a lack of technical-economic development), so they need to import resources and then are classified as importers (“Im”). This characteristic pulls them toward the “Im” vertex of the ternary diagram, which moves them away from the more sustainable ESI* lines, since “Im” resources are by definition nonrenewable resources from a larger economy. It is interesting to note that some states recognized as having high economic vitality (for instance São Paulo #25, Rio de Janeiro #19, Rio Grande do Sul #21 and Paraná #16) are able to extract and produce their own needed resources for housing projects rather than import them, however the majority of these resources are classified as natural nonrenewable “N”, which results in low ESI* performance close to the “N” vertex. For instance, the main N resources for these states are Brick, Sand, Steel/Iron, Granite and Wallboard. Overall, the sustainability performance of the R1 project should not be considered to be good, since the majority of states are below the ESI* = 1 line. The best performance for the R1 project is seen in Amapá (3), Amazonas (4), and Roraima (23).

A similar discussion can be presented for the PP4 and PIS projects, except for some specific differences. For instance, the ESI* of PP4 for all states decreased compared to the R1 project: Roraima (23), Maranhão (10), Mato Grosso (11), Pará (14) and Minas Gerais (13) now show poorer performance with an ESI* below the ESI* = 1 line, indicating unsustainability. In addition, PP4 projects in all other states (except for Amapá #3 and Amazonas #4) are unsustainable. Regarding PIS, Roraima (23) obtained ESI* higher than 1 in addition to states #3 and #4, which are also above ESI* = 1 line in the PP4 ternary diagram. It can also be observed that all states moved in direction toward the “Im” vertex, indicating that PP4 and PIS projects for all states are slightly more dependent on imported resources than the R1 project.

Analyzing all three graphs at the same time and considering even small differences in the ESI* performance of all projects and states, it can be said that the R1 project should be promoted in all states rather than PP4 and PIS projects when considering overall sustainability, because it has higher ESI*. However, the differences between the highest and lowest ESI* performance of the three types of housing projects for the same state implies an insignificant difference considering all sources of error in the method; and this calls for further uncertainty analysis of the method. For instance, Amapá #3 had ESI* values of 2.80, 1.41, and 1.93 for the R1, PP4 and PIS projects respectively; for all of them 1 < ESI* < 5, which shows moderate sustainability. Thus, another possible interpretation is that all projects have similar ESI* performance

Table 3
Emergy table for the building for social interest (PIS) project under a Brazilian national context.

Item[a]	Description	Amount	Unit/m^2	UEV[b] (sej/unit)	Emergy in sej/m^2	Emergy in %
1	Solar radiation	9.45E+04	J	1.00E+00	9.45E+04	< 0.1
2	Wind	8.42E+04	J	2.45E+03	2.06E+08	< 0.1
3	Wood (renew.)	6.12E+00	kg	2.40E+12	1.47E+13	0.2
4	Electricity (renew.)	1.28E+09	J	1.47E+05	1.88E+14	2.4
5	Labor (renew.)	1.04E+01	h	1.77E+13	1.84E+14	2.3
6	Soil loss	1.44E-03	J	1.24E+05	1.79E+02	< 0.1
7	Electricity (non-renew.)	1.19E+09	J	1.47E+05	1.75E+14	2.2
8	Wood (non-renew.)	4.44E+00	kg	2.40E+12	1.07E+13	0.1
9	Steel	1.06E+02	kg	7.81E+12	8.28E+14	10.4
10	Copper	8.17E-01	kg	1.04E+14	8.50E+13	1.1
11	Sand	6.87E+02	kg	1.68E+12	1.15E+15	14.6
12	Brick	3.95E+02	kg	3.68E+12	1.45E+15	18.3
13	Wares	5.59E+01	kg	4.80E+12	2.68E+14	3.4
14	Cement	3.38E+02	kg	3.04E+12	1.03E+15	13.0
15	Glass	1.90E+00	kg	1.41E+12	2.68E+12	< 0.1
16	Wallboard	1.37E+02	kg	3.29E+12	4.51E+14	5.7
17	Granite	3.30E+02	kg	2.44E+12	8.05E+14	10.2
18	Asphalt	1.78E+00	kg	2.55E+13	4.54E+13	0.6
19	PVC plastic	1.47E+01	kg	9.86E+12	1.45E+14	1.8
20	Paint (ink)	3.91E+00	kg	2.55E+13	9.97E+13	1.3
21	Water	6.80E+02	kg	3.27E+08	2.22E+11	< 0.1
22	Labor (non-renew.)	1.54E+01	h	1.77E+13	2.73E+14	3.4
23	Trucks for transportation	4.00E-01	km	9.42E+10	3.77E+10	< 0.1
24	Diesel	6.20E+08	J	1.81E+05	1.12E+14	1.4
25	Labor (renew.)	1.01E-02	h	1.77E+13	1.79E+11	< 0.1
26	Labor (non-renew.)	1.50E-02	h	1.77E+13	2.66E+11	< 0.1
27	Landfill	1.99E+02	kg	1.97E+10	3.92E+12	< 0.1
28	Diesel	6.20E+08	J	1.81E+05	1.12E+14	1.4
29	Trucks for transportation	4.00E-01	km	9.42E+10	3.77E+10	< 0.1
30	Labor (renew.)	6.90E+00	h	1.77E+13	1.22E+14	1.5
31	Labor (non-renew.)	2.06E+01	h	1.77E+13	3.65E+14	4.6
Total emergy for the building for social interest (PIS):					7.93E+15	100.0

[a] Calculation details at Appendix A.
[b] UEVs at Appendix B.

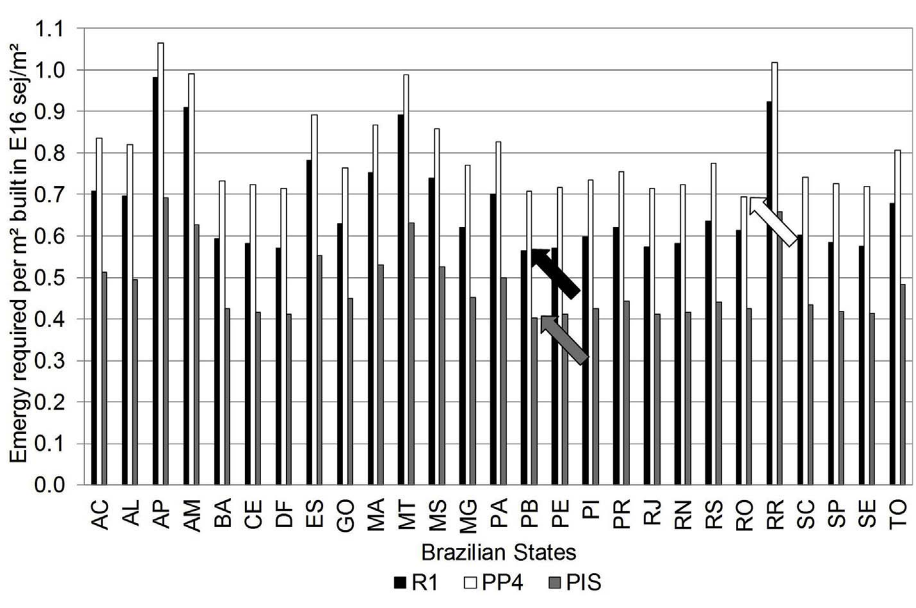

Fig. 7. Emergy required per m^2 of building constructed (in sej/m^2) for the three evaluated social housing projects according to the state in which they are located. Acronyms for Brazilian states are given in Table 4 Arrows indicates the best performance obtained by each of three social housing projects.

for a state, thus, whatever the chosen project for a state, it would result in the highest ESI* possible for that type of construction; maybe due to local availability of natural resources.

As expected, while the emergy required per m^2 built (Fig. 7) indicates that PIS projects should be promoted, the ESI* supports R1 as the most environmental sustainable choice. This result creates difficulties for decision-makers, which is usual when a multicriteria approach is considered as a scientific method to calculate indicators; and this could be even more complex if other economic and social aspects were taken into account. However, according to the objectives of this work, the chosen social housing project to be implemented in each of the 27 Brazilian states should be the one with higher performance based on emergy required per m^2 of building constructed and ESI*, simultaneously. This discussion is presented in the next section.

3.3. Choosing the most sustainable type of social housing project

At this point, two indicators from emergy accounting have been

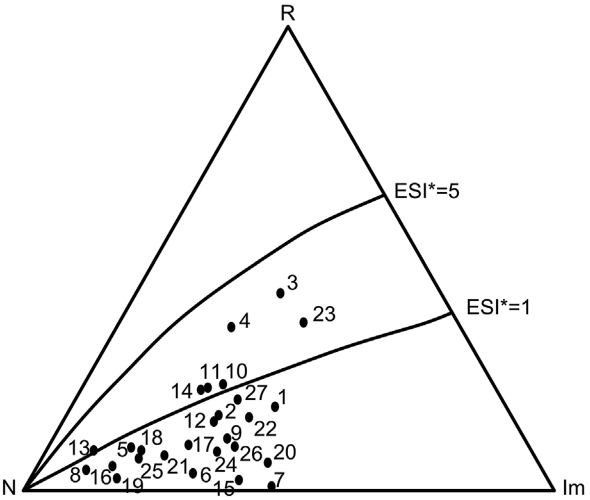

Fig. 8. Ternary emergy diagram for popular housing project (R1). Legend for Brazilian states: 1- Acre, 2- Alagoas, 3- Amapá, 4- Amazonas, 5- Bahia, 6- Ceará, 7- Distrito Federal, 8- Espírito Santo, 9- Goiás, 10- Maranhão, 11- Mato Grosso, 12- Mato Grosso do Sul, 13- Minas Gerais, 14- Pará, 15- Paraíba, 16- Paraná, 17- Pernambuco, 18- Piauí, 19- Rio de Janeiro, 20- Rio Grande do Norte, 21- Rio Grande do Sul, 22- Rondônia, 23- Roraima, 24- Santa Catarina, 25- São Paulo, 26- Sergipe, 27- Tocantins.

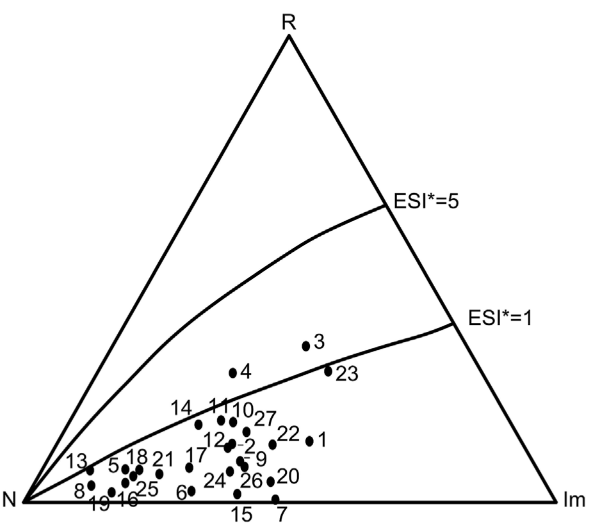

Fig. 9. Ternary emergy diagram for popular building (PP4) project. Legend for Brazilian states at Fig. 8.

considered to support a choice among the three types of social housing projects to move towards sustainability: EICP or its inverse and ESI*. Both indicators were assessed individually and the best options identified, however, as expected, different results were obtained because each emergy indicator has a different framework for calculation and assessment goals. As the main objective of this work is to find the best choice considering both emergy indicators at the same time, Fig. 11 was elaborated in an attempt to support this choice. It is well known that the ESI* index has the so-called regions of sustainability as previous discussed (ESI* < 1, 1 < ESI* < 5, and ESI* > 5), however, the results presented by the ternary diagram in Figs. 8–10 point out that a maximum of 7 Brazilian states from a total of 27 were able to build social housing projects with moderate sustainability (1 < ESI* < 5), and this indicates an overall low level of performance. Thus, instead of considering the ESI* regions of sustainability, Fig. 11 considers the statistical median value of ESI* from all the 81 emergy evaluations aiming to reveal differences among them and to support a better choice regarding the most sustainable project for each Brazilian state. The same approach is considered for the EICP, because it does not have reference numbers that can be used for comparisons as the ESI* does.

Information that can be drawn from Fig. 11 is as follows: (i) all three social housing projects have a similar distribution for their ESI* performance, (ii) PP4 showed the worst performance compared to other social housing projects because, for all states, their diamond symbols are located to the left of the median EICP line and half of them are below the ESI* median line, and (iii) compared to R1 and PP4, the PIS project has a higher amount of its square symbols in the target area with higher ESI* and EICP values. For some states, Fig. 11 clearly identifies the best choice among the social housing projects, because they are located in quadrant "c", indicating that higher ESI* and EICP are found simultaneously. For instance, this applies to Alagoas AL, Amazonas AM, Bahia BA, Maranhão MA, Minas Gerais MG, Mato Grosso MT, Mato Grosso do Sul MS, Pará PA, Paraná PR, and Tocantins TO.

Although these states can be easily identified, the best option for social housing for all the other states are not located at quadrant "c" and thus decision-makers will need further verification to determine the best choice by considering the areas in Fig. 11 within which they fall and the most important regional goals with respect to ESI* and EICP. Considering that understanding these area-related relations for all other symbols in Fig. 11 could make the interpretation of that figure difficult, Table 4 provides the final numbers in table form. According to the criteria used in this work, quadrant "c" is the best option, followed by the highest area obtained in quadrants "b" or "d", and quadrant "a" is avoided because it means low sustainability and low productivity. Table 4 indicates the chosen social housing projects for each Brazilian state. The PIS project was most often chosen, more precisely it was the best choice in 22 of 27 states. The R1 project was chosen to be implemented in 5 states, while PP4 was revealed be the worst choice for all Brazilian states as judged by both criteria, having both lower performance for environmental sustainability and lower construction productivity.

Answering the first research question of this work ("Are there differences in the sustainability performance among the three types of social housing projects R1, PP4, and PIS implemented in the Brazilian states?"), results show that there are differences among the three regarding their environmental sustainability (these are clearly identified at Figs. 8–10). This result is due to differences in the kind and amount of emergy flows supporting the systems due to differences in the partial renewability of the flows supporting each state, and the resources exchanged between states. These characteristics influencing the results can be viewed and understood only after considering both local and regional scales of assessment. In this sense, the scale of analysis should be considered an important aspect, mainly in countries with large territories such as Brazil, which has regional differences in social, environmental, economic, cultural, and other aspects that directly act on the performance of any production system. Although considering different production systems (milk production rather than social housing), Vigne et al. [49] have also discussed the importance of considering different scales in emergy analysis and its influence on final indicators.

In addition to indicators of environmental sustainability, the EICP shows different performance among the three types of social housing projects for each state (Fig. 11). However, trying to provide scientific-based subsidies for decision makers regarding what should be the chosen project to be implemented in each Brazilian state, Table 4 presents the chosen projects considering the maximization of environmental sustainability and productivity. This answers the second research question of this work ("What social housing project should be chosen for each Brazilian state to move towards higher sustainability?"). The results of this study imply that choosing a unique project for all states or even different projects based exclusively on economic issues could be considered as premature and result in loss of the opportunity to maximize sustainability for social housing national programs.

According to Odum [20], systems of any kind and scale have a circular behavior and pulsate, they differ in the pulse size and

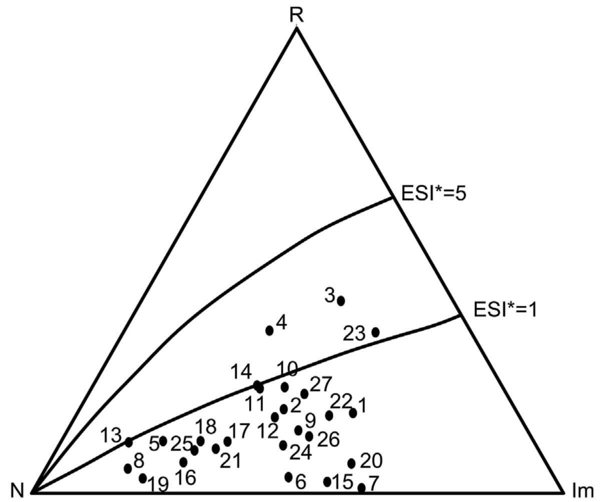

Fig. 10. Ternary emergy diagram for building for social interest (PIS) project. Legend for Brazilian states at Fig. 8.

frequency; for the environmental-economic systems on the global scale, its pulse is that of modern society. Odum and Odum [50] emphasize that different politics or planning should be implemented for the different curve-phases that include growth, climax, descent and stabilization with lower resources. According to some authors [51], society is currently facing the "peak of everything" including fossil fuel, water, fertile soil, biodiversity, and so on, and this is a characteristic of the descent phase of the pulsing curve. Thus, different politics should be considered in this phase, in which business as usual is not an option for a resource-limited world. Specifically for the building sector, which demands a paramount quantity of resources for its functioning, the economic approach should not be considered exclusively to support important decisions regarding sustainable development; mainly for housing projects that have an important social aspect behind them and demand public monetary resources to subsidize their implementation. In this sense, biophysical indicators such as those from emergy accounting used in this work should be viewed as important in supporting decisions to move society towards more sustainable development alternatives.

The National System for Social Housing [8] promotes access of the poorest population into urban lands through economic subsidies for sustainable housing. However, Rubin and Bolfe [52] argue that the sustainability of social housing projects should also consider the real needs of those sheltered families, by providing basic sanitation, accessibility and mobility, sociocultural and environmental adaptability, among other things. Historically, housing projects in Brazil are related to public policies that do not consider a holistic perspective on the housing deficit; an exclusive political-economic aspect is usually considered for a decision. As a result, the real problem of the social housing deficit is neglected and the implemented projects mainly generate profit for private building companies. Although providing strong evidence regarding the different environmental performances of three types of social housing projects implemented in the Brazilian states, the decision regarding the choice of one project rather than another should also consider additional indicators from economic and social dimensions under the general concept of sustainability; and this need could be considered as a limiting factor of this work.

Economic and social aspects were not evaluated here, instead, the environmental dimension (under the conceptual model for strong sustainability) is considered aiming to show that a choice should not be exclusively economic and that different scales of evaluation provide different results. This work has no intention to end the discussion of such important topics, instead, the main idea is to promote a critical and deeper scientific-based discussion on the social housing national programs that are closely related to the country's sustainable development.

4. Conclusions

According to the methods applied in this work, it can be concluded that there are differences in the emergy sustainability index (ESI*) of each type of social housing project evaluated under both perspectives used: (i) individually, when viewed as the average values for Brazil, and (ii) when considering the projects implemented in each of the 27 Brazilian states. The same conclusion is obtained for the emergy index of construction productivity (EICP) evaluated in m^2/sej.

Trying to maximize decisions based on both indicators (ESI* and EICP), the social housing project named building for social interest (PIS) should be implemented in the majority of Brazilian states (22 states precisely), followed by popular housing project (5 states). Popular building (PP4) showed the worst performance for both emergy indicators and thus it should not be supported in any state under an emergy accounting perspective.

In addition to specific results for the evaluated case studies, this work contributes towards a more precise emergy accounting by putting

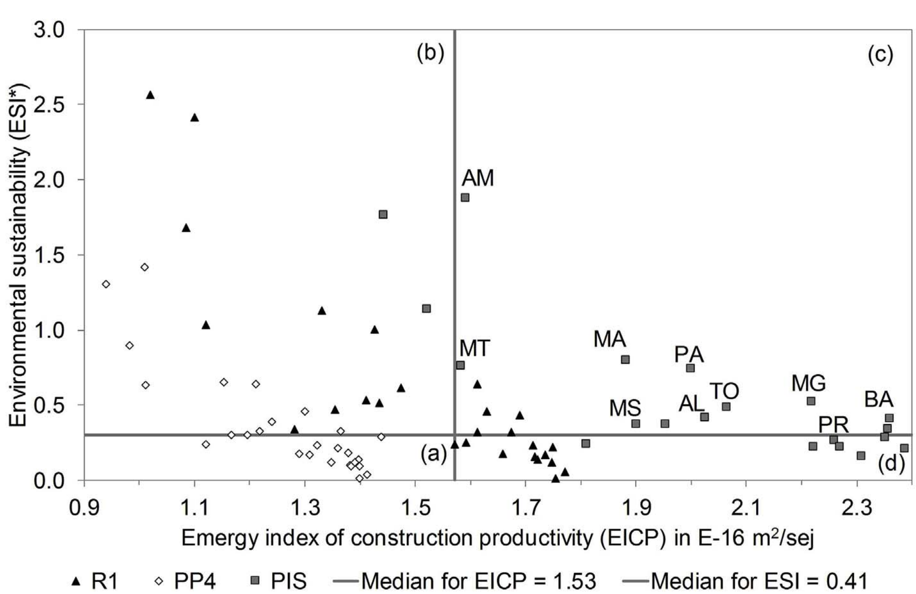

Fig. 11. Relationship between environmental sustainability (ESI*) and the emergy index of construction productivity (EICP) for the three types of social housing projects evaluated for each of the 27 Brazilian states. Legend: AL = Alagoas; AM = Amazonas; BA = Bahia; MA = Maranhão; MG = Minas Gerais; MT = Mato Grosso; MS = Mato Grosso do Sul; PA = Pará; PR = Paraná; TO = Tocantins; (a), (b), (c) and (d) refers to the sustainability regions presented at Fig. 5.

Table 4
The chosen social housing project for each of 27 Brazilian states according to the criteria of highest environmental sustainability and highest emergy index of construction productivity obtained in Fig. 11.

Brazilian states		Selected social housing project	Criteria
1	Acre (AC)	R1	Highest area at quadrant (b)
2	Alagoas (AL)	PIS	Quadrant (c)
3	Amapá (AP)	R1	Highest area at quadrant (b)
4	Amazonas (AM)	PIS	Quadrant (c)
5	Bahia (BA)	PIS	Quadrant (c)
6	Ceará (CE)	R1	Highest area at quadrant (d)
7	Distrito Federal (DF)	PIS	Highest area at quadrant (d)
8	Espírito Santo (ES)	PIS	Highest area at quadrant (d)
9	Goiás (GO)	PIS	Highest area at quadrant (d)
10	Maranhão (MA)	PIS	Quadrant (c)
11	Mato Grosso (MT)	PIS	Quadrant (c)
12	Mato Grosso do Sul (MS)	PIS	Quadrant (c)
13	Minas Gerais (MG)	PIS	Quadrant (c)
14	Pará (PA)	PIS	Quadrant (c)
15	Paraíba (PB)	PIS	Highest area at quadrant (d)
16	Paraná (PR)	PIS	Quadrant (c)
17	Pernambuco (PE)	R1	Highest area at quadrant (d)
18	Piauí (PI)	PIS	Highest area at quadrant (d)
19	Rio de Janeiro (RJ)	PIS	Highest area at quadrant (d)
20	Rio Grande do Norte (RN)	PIS	Highest area at quadrant (d)
21	Rio Grande do Sul (RS)	PIS	Highest area at quadrant (d)
22	Rondônia (RO)	PIS	Highest area at quadrant (d)
23	Roraima (RR)	R1	Highest area at quadrant (b)
24	Santa Catarina (SC)	PIS	Highest area at quadrant (d)
25	São Paulo (SP)	PIS	Highest area at quadrant (d)
26	Sergipe (SE)	PIS	Highest area at quadrant (d)
27	Tocantins (TO)	PIS	Quadrant (c)

into discussion (i) the importance of considering the exchange of resources between regions to support a resource labeling procedure as local or imported, and (ii) by considering the regional partial renewability that has influence on the renewability of local resources. Both approaches are seen as strongly related to the obtained final emergy indices and thus deserve attention.

Acknowledgements

The authors wish to thank the Vice-Reitoria de Pós-graduação da Universidade Paulista (UNIP), the Universidade Federal do Maranhão (UFMA), the CNPq Brasil (proc. 307422/2015-1), and the Beijing Normal University within the framework of the National High-end Foreign Experts Recruitment Program in China. We would like to thank the anonymous reviewers for their very helpful comments and suggestions, which did improve the manuscript.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2017.10.033.

Appendix A. Calculation procedures and raw data for emergy Tables 1–3

Table A.1
Items classification as used in the three social housing projects evaluated in this work.

Standardized items needed per square meter built[a]	Classification[b]	Unit/m^2	R1[a]	PP4[a]	PIS[a]
Laminated plywood 18 mm 2.20 × 1.10 m	Wood	m^2	1.41	0.83	0.70
Steel CA-50	Steel	kg	14.09	18.73	7.68
Concrete fck = 25 MPa	Cement, sand and crushed stone	m^3	0.23	0.28	0.09
Cement CP-32 II	Cement	kg	56.41	57.93	40.91
Sand	Sand	m^3	0.17	0.18	0.13
Crushed stone n°.2	Crushed stone	m^3	–	–	–
Clay Bricks 9cm × 19cm × 19 cm	Bricks	Unit	58.58	60.83	–
Concrete Bricks w/o structural function 19 × 19 × 39 cm	Cement	Unit	–	1.36	14.40
Corrugated fibrocement roofing tile 6 mm 2.44 × 1.10 m	Cement	m^2	2.86	0.42	0.20
Internal door 0.60 × 2.10 m	Wood	Unit	0.11	0.09	0.17
Sliding squared 2.00 × 1.40 m in 4 sheets, anodized aluminum	Iron	m^2	–	–	–
Sliding window 1.20 m × 1.20 m in 2 sheets, folded iron plate n °20	Iron	m^2	0.24	0.32	0.18
Internal door lock, type IV (55 mm), in iron, chrome finish	Iron	Unit	0.12	0.09	0.08
Ceramic tile (tile) 30 cmx40 cm, PEI II	Ware	m^2	1.89	1.85	0.20
White marble countertop 2.00m × 0.60 × 0.02 m	Granite	Unit	0.01	0.01	0.03

Smooth plasterboard 0.60 × 0.60 m	Wallboard	m^2	2.47	2.54	2.14
Transparent plain glass 4 mm	Glass	m^2	0.13	0.18	0.11
PVA latex paint	Paint	L	1.94	2.34	2.57
Waterproofing asphalt emulsion	Asphalt	kg	1.23	1.78	0.73
Copper anti-flame wire, insulation 750 V, 2.5 mm^2	Copper	m	15.59	36.70	35.20
Tripolar circuit breaker 70A	PVC plastic	Unit	0.08	0.37	0.43
White Sanitary Device with Coupled Box	Ware	Unit	0.06	0.04	0.04
Chromed Pressure Water Tap 1/2 ″	Iron	Unit	0.18	0.28	0.20
Galvanized iron pipe 2 1/2 ″	Iron	m	0.01	0.31	0.24
PVC pipe for sewage 150 mm	PVC plastic	m	0.52	0.59	0.55
Construction worker	Work hours	h	36.16	30.58	24.60
Engineering	Service ($)	h	1.65	0.44	0.41
Rental of concrete mixer 320 L	Iron	day	0.28	0.27	0.14

[a] Source: ABNT [7].
[b] Our assumption.

Calculation details for the emergy table (Table 1) of popular housing (R1, 58.64m²)

#1 Solar radiation. Input needed to dry concrete and allow structural properties. It refers to solar radiation in 1 m^2 of constructed housing during the period demanded to construct that 1 m^2. Area for reference = 1 m^2; Insolation, Brazilian average = 1.57 kcal/cm^2/yr; Albedo = 30%; Effective working hours for 1 m^2 of the R1 housing = 26.44 h/m^2; Conversion = (m^2) (kcal/cm^2/yr) (1-albedo/100) (10,000 cm^2/m^2) (4186 J/kcal) (26.44 h/m^2)/(8760 h/yr); Amount = 1.39E5 J/m^2;
#2 Wind (kinetic energy). Wind needed to dry concrete and allow structural properties. It refers to wind energy applied in 1 m^2 of constructed housing during the period demanded to construct that 1 m^2. Area for reference = 1 m^2; Air density = 1.3 kg/m^3; Geostrophic wind = 10 m/s; Drag coefficient = 0.001; Effective working hours for 1 m^2 of the R1 housing = 26.44 h/m^2; Conversion = (m^2) (kg/m^3) $(m/s)^3$ (0.001) (3.14E7 s/yr) (hr/m^2)/(8760 h/yr); Amount = 1.23E5 J/m^2;
#3 Wood (renewable fraction). Demanded wood = 10.20 kg/m^2; Wood's renewable fraction of 58% from Brown and Ulgiati [53]; Amount = 5.92E0 kg/m^2;
#4 Electricity (renewable fraction). Consumption per 1 m^2 of built house = 6.86E2 kWh/m^2; 52% of all electricity generated and used in Brazil comes from renewable sources; Conversion = (kWh/m^2) (3,600,000 J/kWh) (0.52); Amount = 1.28E9 J/m^2;
#5 Labor (renewable fraction). Total labor hours = 36.2 h/m2; additional 5% for unforeseen; 40.2% of renewability for labor force in Brazil [54]; Amount = 1.53E1 h/m^2;
#6 Soil loss. Soil loss is considered here according to the appropriation issue, i.e. this soil will never be used to produce food that would be its main function. Area for reference = 1 m^2; Soil volume excavated per 1 m^2 for structural purposes = 0.997 m^3/m^2; Soil density = 2.3E-6 g/m^3; Percentage of organic matter = 3%; Energy of organic matter = 5 kcal/g; Conversion = (m^3/m^2) (g/m^3) (0.03) (kcal/g) (4186 J/kcal); Amount = 1.44E-3 J/m^2;
#7 Electricity (non-renewable fraction). Consumption per 1 m^2 of built house = 6.86E2 kWh/m^2; 52% of all electricity generated and used in Brazil comes from renewable sources; Conversion = (kWh/m^2) (3,600,000 J/kWh) (0.48); Amount = 1.19E9 J/m^2;
#8 Wood (non-renewable fraction). Demanded wood = 10.20 kg/m^2; Wood's renewable fraction of 58% from Brown and Ulgiati [53]; Amount = 4.28E0 kg/m^2;
#9 - #21. Values based on numbers provided by Table A.1. and using specific densities for the different materials.
#22 Labor (renewable fraction). Total labor hours = 36.2 h/m2; additional 5% for unforeseen; 59.8% of non-renewability for labor force in Brazil [53]; Amount = 2.27E1 h/m^2;
#23 Trucks for transportation. Focusing on economical purposes, the maximum transport distance between cities is established as 40 km by contractors. This value was also assumed here. Amount = 4.00E-1 km/m^2;
#24 Diesel. Diesel used for transportation. Consumption = 0.325 L/km; Transport distance per 1 m^2 built = 40 km/m^2 (from item #20); Energy content of diesel = 1.14E4 kcal/L; Conversion = (L/km) (km/m^2) (kcal/L) (4186 J/kcal); Amount = 6.20E8 J/m^2;
#25 Labor (Truck driver; renewable fraction). Transport distance per 1 m^2 built = 40 km/m^2 (from item #20); Average truck velocity = 20 km/h; Materials transported = 2330 kg/m^2; Truck capacity = 23,000 kg; R1 area = 58.64 m^2; 40.2% of renewability for labor force in Brazil [54]; Conversion = (km/m^2) (kg) (0.402)/(kg/m^2) (km/h) (m^2); Amount = 1.35E-1 h/m^2;
#26 Labor (Truck driver; non-renewable fraction). Conversion = 3.37E-1 h/m^2 – 1.35E-1 h/m^2 (from #22); Amount = 2.02E-1 h/m^2;
#27 Landfill. Equivalent amount of construction residues = 298 kg/m^2 [54]; including loss of 10% in mass of steel and copper, 13% of brick, 14% of wares and paints, 30% of sand, and 55% of cement.
#28 Diesel. The same consideration as for item #21. Amount = 6.20E8 J/m^2;
#29 Trucks for transportation. Focusing on economical purposes, the maximum transport distance between cities is established as 40 km/m^2 by contractors. This value was also assumed here. Amount = 4.00E-1 km/m^2;
#30 Labor (Truck driver; renewable fraction). Transport distance per 1 m^2 built = 40 km/m^2 (from item #20); Average truck velocity = 20 km/h; Materials transported = 298 kg/m^2; Truck capacity = 23,000 kg; R1 area = 58.64 m^2; 40.2% of renewability for labor force in Brazil [54]; Conversion = (km/m^2) (kg) (0.402)/(kg/m^2) (km/h) (m^2); Amount = 1.06E0 h/m^2;
#31 Labor (Truck driver; non-renewable fraction). Conversion = 2.63E0 h/m^2 – 1.06E0 h/m^2 (from #27); Amount = 1.57E0 h/m^2;

Calculation details for the emergy table (Table 2) of popular building (PP4, 1,415m²)

#1 Solar radiation. Input needed to dry concrete and allow structural properties. It refers to solar radiation in 1 m^2 of constructed housing during the period demanded to construct that 1 m^2. Area for reference = 1 m^2; Insolation, Brazilian average = 1.57 kcal/cm^2/yr; Albedo = 30%;

Effective working hours for 1 m^2 of the PP4 housing = 21.74 h/m^2; Conversion = (m^2) (kcal/cm^2/yr) (1-albedo/100) (10,000 cm^2/m^2) (4186 J/kcal) (21.74 h/m^2)/(8760 h/yr); Amount = 1.14E5 J/m^2;

#2 Wind (kinetic energy). Wind needed to dry concrete and allow structural properties. It refers to wind energy applied in 1 m^2 of constructed housing during the period demanded to construct that 1 m^2. Area for reference = 1 m^2; Air density = 1.3 kg/m^3; Geostrophic wind = 10 m/s; Drag coefficient = 0.001; Effective working hours for 1 m^2 of the PP4 housing = 21.74 h/m^2; Conversion = (m^2) (kg/m^3) $(m/s)^3$ (0.001) (3.14E7 s/yr) (hr/m^2)/(8760 h/yr); Amount = 1.02E5 J/m^2;

#3 Wood (renewable fraction). Demanded wood = 10.54 kg/m^2; Wood's renewable fraction of 58% from Brown and Ulgiati [53]; Amount = 6.11E0 kg/m^2;

#4 Electricity (renewable fraction). Consumption per 1 m^2 of built house = 6.86E2 kWh/m^2; 52% of all electricity generated and used in Brazil comes from renewable sources; Conversion = (kWh/m^2) (3,600,000 J/kWh) (0.52); Amount = 1.28E9 J/m^2;

#5 Labor (renewable fraction). Total labor hours = 30.6 h/m^2; additional 5% for unforeseen; 40.2% of renewability for labor force in Brazil [54]; Amount = 1.29E1 h/m^2;

#6 Soil loss. Soil loss is due to the appropriation issue, i.e. this soil will never be used to produce food that would be its main function. Area for reference = 1 m^2; Soil volume excavated per 1 m^2 for structural purposes = 0.997 m^3/m^2; Soil density = 2.3E-6 g/m^3; Percentage of organic matter = 3%; Energy of organic matter = 5 kcal/g; Conversion = (m^3/m^2) (g/m^3) (0.03) (kcal/g) (4186 J/kcal); Amount = 1.44E-3 J/m^2;

#7 Electricity (non-renewable fraction). Consumption per 1 m^2 of built house = 6.86E2 kWh/m^2; 52% of all electricity generated and used in Brazil comes from renewable sources; Conversion = (kWh/m^2) (3,600,000 J/kWh) (0.48); Amount = 1.19E9 J/m^2;

#8 Wood (non-renewable fraction). Demanded wood = 10.54 kg/m^2; Wood's renewable fraction of 58% from Brown and Ulgiati [53]; Amount = 4.42E0 kg/m^2;

#9 - #21. Values based on numbers provided by Table A.1. and using specific densities for the different materials.

#22 Labor (non-renewable fraction). Total labor hours = 30.6 h/m^2; additional 5% for unforeseen; 59.8% of non-renewability for labor force in Brazil [54]; Amount = 1.92E1 h/m^2;

#23 Trucks for transportation. Focusing on economical purposes, the maximum transport distance between cities is established as 40 km by contractors. This value was also assumed here. Amount = 4.00E-1 km/m^2;

#24 Diesel. Diesel used for transportation. Consumption = 0.325 L/km; Transport distance per 1m2 built = 40 km/m2 (from item #23); Energy content of diesel = 1.14E4 kcal/L; Conversion = (L/km) (km/m2) (kcal/L) (4186 J/kcal); Amount = 6.20E8 J/m2;

#25 Labor (Truck driver; renewable fraction). Transport distance per 1 m^2 built = 40 km/m^2 (from item #20); Average truck velocity = 20 km/h; Materials transported = 2540 kg/m^2; Truck capacity = 23,000 kg; PP4 area = 1415 m^2; 40.2% of renewability for labor force in Brazil [54]; Conversion = (km/m^2) (kg) (0.402)/(kg/m^2) (km/h) (m^2); Amount = 5.14E-3 h/m^2;

#26 Labor (Truck driver; non-renewable fraction). Conversion = 1.27E-2 h/m^2 – 5.14E-3 h/m^2 (from #25); Amount = 7.66E-3 h/m^2;

#27 Landfill. Equivalent amount of construction residues = 320 kg/m^2 [55]; including loss of 10% in mass of steel and copper, 13% of brick, 14% of wares and paints, 15% of sand, and 55% of cement.

#28 Diesel. The same consideration as for item #24. Amount = 6.20E8 J/m^2;

#29 Trucks for transportation. Focusing on economical purposes, the maximum transport distance between cities is established as 40 km/m^2 by contractors. This value was also assumed here. Amount = 4.00E-1 km/m^2;

#30 Labor (Truck driver; renew. fraction). Transport distance per 1 m^2 built = 40 km/m^2 (from item #23); Average truck velocity = 20 km/h; Materials transported = 320 kg/m^2; Truck capacity = 23,000 kg; PP4 area = 1415 m^2; 40.2% of renewability for labor force in Brazil [54]; Conversion = (km/m^2) (kg/m^2) (m^2) (0.402)/(kg) (km/h); Amount = 1.58E1 h/m^2;

#31 Labor (Truck driver; non-renewable fraction). Conversion = 3.93E1 h/m^2 – 1.58E1 h/m^2 (from #29); Amount = 2.35E1 h/m^2;

Calculation details for the emergy table (Table 3) of building for social interest (PIS, 991.45m^2)

#1 Solar radiation. Input needed to dry concrete and allow structural properties. It refers to solar radiation in 1 m^2 of constructed housing during the period demanded to construct that 1 m^2. Area for reference = 1 m^2; Insolation, Brazilian average = 1.57 kcal/cm^2/yr; Albedo = 30%; Effective working hours for 1 m^2 of the PIS = 18.07 h/m^2; Conversion = (m^2) (kcal/cm^2/yr) (1-albedo/100) (10,000 cm^2/m^2) (4186 J/kcal) (18.07 h/m^2)/(8760 h/yr); Amount = 9.45E4 J/m^2;

#2 Wind (kinetic energy). Wind needed to dry concrete and allow structural properties. It refers to wind energy applied in 1 m^2 of constructed housing during the period demanded to construct that 1 m^2. Area for reference = 1 m^2; Air density = 1.3 kg/m^3; Geostrophic wind = 10 m/s; Drag coefficient = 0.001; Effective working hours for 1 m^2 of the PIS = 18.07 h/m^2; Conversion = (m^2) (kg/m^3) $(m/s)^3$ (0.001) (3.14E7 s/yr) (hr/m^2)/(8760 h/yr); Amount = 8.42E4 J/m^2;

#3 Wood (renewable fraction). Demanded wood = 10.56 kg/m^2; Wood's renewable fraction of 58% from Brown and Ulgiati [53]; Amount = 6.12E0 kg/m^2;

#4 Electricity (renewable fraction). Consumption per 1 m^2 of built house = 6.86E2 kWh/m^2; 52% of all electricity generated and used in Brazil comes from renewable sources; Conversion = (kWh/m^2) (3,600,000 J/kWh) (0.52); Amount = 1.28E9 J/m^2;

#5 Labor (renewable fraction). Total labor hours = 24.6 h/m^2; additional 5% for unforeseen; 40.2% of renewability for labor force in Brazil [54]; Amount = 1.04E1 h/m^2;

#6 Soil loss. Soil loss is due to the appropriation issue, i.e. this soil will never be used to produce food that would be its main function. Area for reference = 1 m^2; Soil volume excavated per 1 m^2 for structural purposes = 0.997 m^3/m^2; Soil density = 2.3E-6 g/m^3; Percentage of organic matter = 3%; Energy of organic matter = 5 kcal/g; Conversion = (m^3/m^2) (g/m^3) (0.03) (kcal/g) (4186 J/kcal); Amount = 1.44E-3 J/m^2;

#7 Electricity (non-renewable fraction). Consumption per 1 m^2 of built house = 6.86E2 kWh/m^2; 52% of all electricity generated and used in Brazil comes from renewable sources; Conversion = (kWh/m^2) (3,600,000 J/kWh) (0.48); Amount = 1.19E9 J/m^2;

#8 Wood (non-renewable fraction). Demanded wood = 10.56 kg/m^2; Wood's renewable fraction of 58% from Brown and Ulgiati [53]; Amount = 4.44E0 kg/m^2;

#9 - #21. Values based on numbers provided by Table A.1. and using specific densities for the different materials.

#22 Labor (non-renewable fraction). Total labor hours = 24.6 h/m^2; additional 5% for unforeseen; 59.8% of non-renewability for labor force in Brazil [54]; Amount = 1.54E1 h/m^2;

#23 Trucks for transportation. Focusing on economical purposes, the maximum transport distance between cities is established as 40 km by contractors. This value was also assumed here. Amount = 4.00E-1 km/m^2;
#24 Diesel. Diesel used for transportation. Consumption = 0.325 L/km; Transport distance per 1 m^2 built = 40 km/m^2 (from item #23); Energy content of diesel = 1.14E4 kcal/L; Conversion = (L/km) (km/m^2) (kcal/L) (4186 J/kcal); Amount = 6.20E8 J/m^2;
#25 Labor (Truck driver; renewable fraction). Transport distance per 1 m^2 built = 40 km/m^2 (from item #20); Average truck velocity = 20 km/h; Materials transported = 1850 kg/m^2; Truck capacity = 23,000 kg; PIS area = 991.45 m^2; 40.2% of renewability for labor force in Brazil [54]; Conversion = (km/m^2) (kg) (0.402)/(kg/m^2) (km/h) (m^2); Amount = 1.01E-2 h/m^2;
#26 Labor (Truck driver; non-renewable fraction). Conversion = 2.51E-2 h/m^2 – 1.01E-2 h/m^2 (from #25); Amount = 1.50E-2 h/m^2;
#27 Landfill. Equivalent amount of construction residues = 199 kg/m^2 [55]; including loss of 10% in mass of steel and copper, 13% of brick, 14% of wares and paints, 15% of sand, and 55% of cement.
#28 Diesel. The same consideration as for item #24. Amount = 6.20E8 J/m^2;
#29 Trucks for transportation. Focusing on economical purposes, the maximum transport distance between cities is established as 40 km/m^2 by contractors. This value was also assumed here. Amount = 4.00E-1 km/m^2;
#30 Labor (Truck driver; renew. fraction). Transport distance per 1 m^2 built = 40 km/m^2 (from item #23); Average truck velocity = 20 km/h; Materials transported = 199 kg/m^2; Truck capacity = 23,000 kg; PIS area = 991.45 m^2; 40.2% of renewability for labor force in Brazil [54]; Conversion = (km/m^2) (kg/m^2) (m^2) (0.402)/(kg) (km/h); Amount = 6.90E0 h/m^2;
#31 Labor (Truck driver; non-renewable fraction). Conversion = 2.75E1 h/m^2 – 6.90E0 h/m^2 (from #29); Amount = 2.06E1 h/m^2;

Appendix B. Unit Emergy Values (UEV) used in this work. Emergy baseline of 15.83E24 sej/yr [36]. Values include labor and services

Item	Unit	UEV (sej/Unit)	Reference
Solar radiation	sej/J	1.00E+00	By definition
Wind (kinetic energy)	sej/J	2.45E+03	[36]
Soil loss	sej/J	1.24E+05	[36]
Electricity	sej/J	1.47E+05	[56]
Diesel	sej/J	1.81E+05	[57]
Landfill (discard residues)	sej/kg	1.97E+10	[58]
Wood	sej/kg	2.40E+12	[20]
Steel	sej/kg	7.81E+12	[42]
Water	sej/kg	3.27E+08	[59]
Sand	sej/kg	1.68E+12	[20]
Asphalt	sej/kg	2.55E+13	[58]
Brick	sej/kg	3.68E+12	[58]
Wares (bathroom and kitchen)	sej/kg	4.80E+12	[58]
Cement	sej/kg	3.04E+12	[32]
Copper	sej/kg	1.04E+14	[32]
Iron (rebar)	sej/kg	6.97E+12	[58]
Wallboard	sej/kg	3.29E+12	[32]
Granite	sej/kg	2.44E+12	[32]
PVC plastic	sej/kg	9.86E+12	[58]
Paint (ink)	sej/kg	2.55E+13	[58]
Glass for windows	sej/kg	1.41E+12	[20]
Trucks for transportation	sej/km	9.42E+10	[32]
Labor	–	–	Please see comment (a) below

(a) Labor - UEV for Labor varies according to state being considered for analysis. Brazil has 27 states, so 27 different UEVs for labor were considered. They were estimated by dividing the total emergy driven a specific state by the total inhabitants in that state resulting in sej/inhabitant. All these UEVs were previously assessed by Demetrio [54].

Appendix C. Brazilian states partial renewability of inputs, and the most important resources used by the social housing projects originating from the state

Brazilian states	State partial renewability in %[a]	Material and state producer										
		Wood[b]	Steel[c]	Asphalt[d]	Brick[e]	Cement[f]	Copper[g]	Wall-board[h]	Granite[i]	PVC plastic[g]	Paint[j]	Glass[k]
1- Acre	93	X										
2- Alagoas	48					X						
3- Amapá	98	X										
4- Amazonas	92	X		X		X						
5- Bahia	47		X	X		X			X			
6- Ceará	59		X	X	X	X					X	
7- Distrito Federal	8					X						
8- Espírito Santo	7		X		X	X						

9- Goiás	39					X						
10- Maranhão	77					X		X				
11- Mato Grosso	51	X				X						
12- Mato Grosso do Sul	40					X						
13- Minas Gerais	15	X	X	X	X	X	X		X	X		
14- Pará	76	X	X			X						
15- Paraíba	45				X	X				X		
16- Paraná	14	X	X	X		X				X	X	
17- Pernambuco	34		X		X	X		X			X	
18- Piauí	62					X			X			
19- Rio de Janeiro	30		X	X	X	X			X			X
20- Rio Grande do Norte	73					X						
21- Rio Grande do Sul	27	X	X	X	X	X				X		X
22- Rondônia	80	X				X						
23- Roraima	98	X										
24- Santa Catarina	31	X				X					X	X
25- São Paulo	13	X	X	X	X	X	X		X	X	X	X
26- Sergipe	42					X						
27- Tocantins	74					X						

[a][54]; [b][60]; [c][61]; [d][62]; [e][63]; [f][64]; [g][65]; [h][66]; [i][67]; [j][68]; [k][69].

References

[1] A. Sharma, A. Saxena, M. Sethi, V. Shree, Varun, Life cycle assessment of buildings: a review, Renew. Sustain. Energy Rev. 15 (2011) 871–875.

[2] Agenda 21 for Sustainable Construction in Developing Countries – a Discussion Document, the International Council for Research and Innovation in Building and Construction (CIB), United Nations Environment Programme (UNEP), International Environmental Technology Centre (UNEP-IETC), (2002) 2002 http://www.unep.or.jp/ietc/Focus/Agenda%2021%20BOOK.pdf/ accessed 12-03-17.

[3] J.S. Paulsen, R.M. Sposto, A life cycle energy analysis of social housing in Brazil: case study for the program “MY HOUSE MY LIFE”, Energy Build. 57 (2013) 95–102.

[4] Annual report on construction industry (PAIC) 2012/2014, Brazilian Institute of Geography and Statistics (IBGE), (2017) accessed 12-03-17 http://www.ibge.gov.br/.

[5] Brazilian Committee for the Construction Sector (CBIC), (2017) accessed 12-03-17 http://www.cbicdados.com.br/menu/pib-e-investimento/pib-brasil-e-construcao-civil/.

[6] Portal Brasil, Minha Casa Minha Vida (Governmental Information about Social Housing Projects in Brazil), (2016) accessed 12-03-17 http://www.brasil.gov.br/infraestrutura/minha-casa-minha-vida/.

[7] Brazilian association for technical rules, ABNT NBR 12721, Evaluation for Unit Costs and Elaborations of Construction Budget for Incorporation of Joint Ownership Building, (2016) accessed 12-03-17 http://www.abntcatalogo.com.br/norma.aspx?ID=4743/.

[8] National system for social housing (NSSH), Brazilian Law 11,124 of June 16th 2005, (2005) accessed 12-03-17 http://www.planalto.gov.br/ccivil_03/_ato2004-2006/2005/lei/l11124.htm/.

[9] D. Sanfelici, L. Halbert, Financial markets, developers and the geographies of housing in Brazil: a supply-side account, Urban Stud. 53 (2016) 1465–1485.

[10] M.A. Triana, R. Lamberts, P. Sassi, Characterization of representative building typologies for social housing projects in Brazil and its energy performance, Energy Policy 87 (2015) 524–541.

[11] E. Zea Escamilla, G. Habert, E. Wohlmuth, When CO_2 counts: sustainability assessment of industrialized bamboo as an alternative for social housing programs in the Philippines, Build. Environ. 103 (2016) 44–53.

[12] V. Puri, P. Chakrabortty, S. Anand, S. Majumdar, Bamboo reinforced prefabricated wall panels for low cost housing, J. Build. Eng. 9 (2017) 52–59.

[13] J. Monahan, J.C. Powell, An embodied carbon energy analysis of modern methods of construction in housing: a case study using lifecycle assessment framework, Energy Build. 43 (2011) 179–188.

[14] F.S.S. Scheidt, P.R. Silva, S.M.C.P. Silva, E.H. Hirota, Considering environmental requirements in low-income housing projects: a case study, Ambiente Construído 10 (2010) 91–106.

[15] H. Yi, R.S. Srinivasan, W.W. Braham, An integrated energy-emergy approach to building form optimization: use of energyplus, emergy analysis and taguchi-regression method, Build. Environ. 84 (2015) 89–104.

[16] R.S. Srinivasan, W. Ingwersen, C. Trucco, R. Ries, D. Campbell, Comparison of energy-based indicators used in life cycle assessment tools for buildings, Build. Environ. 79 (2014) 138–151.

[17] R.M. Pulselli, E. Simoncini, N. Marchettini, Energy and emergy based cost–benefit evaluation of building envelopes relative to geographical location and climate, Build. Environ. 44 (2009) 920–928.

[18] A. Scipioni, A. Mazzi, M. Mason, A. Manzrdo, The dashboard of sustainability to measure the local urban sustainable development: the case study of Padua municipality, Ecol. Indic. 9 (2009) 364–380.

[19] State of play of sustainable building in Latin America 2014, Sustainable Buildings and Climate Initiative, United Nations Environmental Programme (UNEP), (2014) accessed 12-03-17 http://www.unep.org/sbci/pdfs/State%20of%20Play%20Sustainable%20Buildings%20LA2014%20_ENG.pdf/.

[20] H.T. Odum, Environmental Accounting, Emergy and Environmental Decision-making, John Wiley & Sons Inc, NY, 1996.

[21] M.T. Brown, S. Ulgiati, Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation, Ecol. Eng. 9 (1997) 51–69.

[22] D.E. Campbell, A.S. Garmestani, An energy systems view of sustainability: emergy evaluation of the San Luis Basin, Colorado, J. Environ. Manag. 95 (2012) 72–97.

[23] B.F. Giannetti, C.M.V.B. Almeida, F. Agostinho, S.H. Bonilla, S. Ulgiati, Primary evidences on the robustness of environmental accounting from emergy, J. Environ. Account. Manag. 1 (2013) 203–212.

[24] H. Yi, W.W. Braham, Uncertainty characterization of building emergy analysis (BEmA), Build. Environ. 92 (2015) 538–558.

[25] R.S. Srinivasan, W.W. Braham, D.E. Campbell, C.D. Curcija, Re(De)fining net zero energy: renewable emergy balance in environmental building design, Build. Environ. 47 (2012) 300–315.

[26] F. Agostinho, L. Pereira, Support area as an indicator of environmental load: comparison between embodied energy, ecological footprint, and emergy accounting methods, Ecol. Indic. 24 (2013) 494–503.

[27] UNEP-sbci Annual Report 2013/14, Sustainable Buildings and Climate Initiative United Nations Environmental Programme, (2017) accessed 12-03-17 http://staging.unep.org/sbci/pdfs/Annual%20Report%202013%20-%202014.pdf/.

[28] Global Building Performance Network (GBPN), (2013) accessed 12-03-17 http://www.gbpn.org/reports/.

[29] International Energy Outlook, (2016) accessed 12-03-17 https://www.eia.gov/outlooks/ieo/pdf/buildings.pdf/.

[30] H. Rothrock, Sustainable housing: emergy evaluation of an off-grid residence, Energy Build. 85 (2014) 287–292.

[31] Y. Geng, P. Zhang, S. Ulgiati, J. Sarkis, Emergy analysis of an industrial park: the case of Dalian, China, Sci. Total Environ. 408 (2010) 5273–5283.

[32] R.M. Pulselli, E. Simoncini, F.M. Pulselli, S. Bastianoni, Emergy analysis of building manufacturing, maintenance and use: em-building indices to evaluate housing sustainability, Energy Build. 39 (2007) 620–628.

[33] D.E. Campbell, H. Lu, H.A. Walker, Relationships among the energy, emergy, and money flows of the United States from 1900 to 2011, Front. Energy Res. 2 (41) (2014) 1–31.

[34] H.T. Odum, Ecological and General Systems: an Introduction to Systems Ecology, University Press of Colorado, 1994, p. 644 Revised edition.

[35] S. Ulgiati, M.T. Brown, Labor and services as information carriers in emergy-LCA accounting, J. Environ. Account. Manag. 2 (2014) 163–170.

[36] H.T. Odum, Folio #2 Emergy of Global Processes, Handbook of Emergy Evaluation, Center for Environmental Policy, University of Florida, Gainesville, 2000.

[37] M.T. Brown, D.E. Campbell, C. De Vilbiss, S. Ulgiati, The geobiosphere emergy baseline: a synthesis, Ecol. Model. 339 (2016) 92–95.

[38] D.E. Campbell, Emergy baseline for the Earth: a historical review of the science and

a new calculation, Ecol. Model. 339 (2016) 96–125.
[39] S.H. Bonilla, R.L. Guarnetti, C.M.V.B. Almeida, B.F. Giannetti, Sustainability assessment of a giant bamboo plantation in Brazil: exploring the influence of labour, time and space, J. Clean. Prod. 18 (2010) 83–91.
[40] C.M.V.B. Almeida, A.J.M. Rodrigues, S.H. Bonilla, B.F. Giannetti, Emergy as a tool for Ecodesign: evaluating materials selection for beverage packages in Brazil, J. Clean. Prod. 18 (2010) 32–43.
[41] B.F. Giannetti, J.F.C. Demétrio, S.H. Bonilla, F. Agostinho, C.M.V.B. Almeida, Emergy diagnosis and reflections towards Brazilian sustainable development, Energy Policy 63 (2013) 1002–1012.
[42] M.T. Brown, S. Ulgiati, Emergy analysis and environmental accounting, Encycl. Energy 2 (2004) 329–354.
[43] B.F. Giannetti, F.A. Barrella, C.M.V.B. Almeida, A combined tool for environmental scientists and decision makers: ternary diagrams and emergy accounting, J. Clean. Prod. 14 (2006) 201–210.
[44] A. Gasparatos, M. El-Haram, M. Horner, A critical review of reductionist approaches for assessing the progress towards sustainability, Environ. Impact Assess. Rev. 28 (2008) 286–311.
[45] C.M.V.B. Almeida, F.A. Barrella, B.F. Giannetti, Emergetic ternary diagram: five examples for application in environmental accounting for decision-making, J. Clean. Prod. 15 (2007) 63–74.
[46] J.G.A. Carvalho, Environmental Accounting of a Construction, M.Sc. dissertation Paulista University (UNIP), Brazil, 2010.
[47] B. Reza, R. Sadiq, K. Hewage, Emergy-based life cycle assessment (Em-LCA) of multi-unit and single residential buildings in Canada, Int. J. Sustain. Built Environ. 3 (2014) 207–224.
[48] H. Yi, R.S. Srinivasan, W.W. Brahan, D.R. Tilley, An ecological understanding of net-zero energy building: evaluation of sustainability based on emergy theory, J. Clean. Prod. 143 (2017) 654–671.
[49] M. Vigne, J. Peyraud, P. Lecomte, M.S. Corson, A. Wilfart, Emergy evaluation of contrasting dairy systems at multiple levels, J. Environ. Manag. 129 (2013) 44–53.
[50] H.T. Odum, E.C. Odum, A Prosperous Way Down: Principles and Policies, University Press of Colorado, 2008, p. 344.
[51] C.A.S. Hall, J.W. Day Jr., Revisiting the limits to growth after peak oil, Am. Sci. 97 (2009) 230–237.
[52] G.R. Rubin, S.A. Bolfe, The development of social housing in Brazil (paper in Portuguese), Ciência Nat. 36 (2015) 201–213.
[53] M.T. Brown, S. Ulgiati, Emergy evaluations and environmental loading of electricity production systems, J. Clean. Prod. 10 (2002) 321–334.
[54] F.J.C. Demetrio, Assessment of the Brazilian Environmental Sustainability Using Emergy Accounting, Ph.D. dissertation Paulista University (UNIP), Brazil, 2011.
[55] D.M. Prado, Physical and Mechanical Properties of Structural Blocks Produced with Recycled Aggregates of Concrete, M.Sc. dissertation São Paulo University, Brazil, 2006.
[56] B.F. Giannetti, F. Agostinho, L.C. Moraes, C.M.V.B. Almeida, S. Ulgiati, Multicriteria cost–benefit assessment of tannery production: the need for breakthrough process alternatives beyond conventional technology optimization, Environ. Impact Assess. Rev. 54 (2015) 22–38.
[57] M.T. Brown, G. Protano, S. Ulgiati, Assessing geobiosphere work of generating global reserves of coal, crude oil, and natural gas, Ecol. Model. 222 (2011) 879–887.
[58] M.T. Brown, V. Buranakarn, Emergy indices and ratios for sustainable material cycles and recycle option, Resources, Conservation Recycl. 38 (2003) 1–22.
[59] A.A. Buenfil, Emergy Evaluation of Water, PhD Thesis University of Florida, USA, Gainesville, 2001.
[60] Statistical Brazilian Yearbook V74, Brazilian Institute of Geography and Statistics (IBGE), (2014) accessed 12-03-17 http://biblioteca.ibge.gov.br/visualizacao/periodicos/20/aeb_2014.pdf/.
[61] Steel Brazilian Institute (AçoBrasil), (2016) accessed 12-03-17 http://www.acobrasil.org.br/site2015/.
[62] Industries Federation of São Paulo State (FIESP), (2017) accessed 12-03-17 http://www.fiesp.com.br/.
[63] Ministry of Mines and Energy (MME), Development of Studies to Elaborate the Strategic Plan (2010-2030) on Geology, Mining and Mineral Transformation, (2009) accessed 12-03-17 http://www.mme.gov.br/.
[64] Brazilian Syndicate of Cement Industry (SNIC), (2008) accessed 12-03-17 http://www.snic.org.br/pdf/relat2008-9web.pdf/.
[65] Brazilian Association of Electronic Industry (ABNEE), (2017) accessed 12-03-17 http://www.abinee.org.br/abinee/associa/equil.htm/.
[66] L. Peres, M. Benachour, V.A. Santos, Gesso: produção e utilização na construção civil (Wallboard: production and utilization on building sector), Recife, SEBRAE, 2008 (Book in Portuguese language).
[67] Brazilian Network Information on Productive Local Arrangements (PLA) of Mineral Base - Current Situation of PLA for Mineral Industry, (2010) accessed 12-03-17 http://www.cetem.gov.br/workshop/palestras/OLIVEIRA_2010_ATUACAO_%20GOVERNAMENTAL_NAS_APLS.pdf/.
[68] Brazilian Association for Ink Industries (ABRAFATI), (2012) accessed 12-03-17 http://www.abrafati.com.br/associados/.
[69] Brazilian Association for Distributors and Processors of Flat Glass (ABRAVIDRO), (2012) edition nº 473 https://app.magtab.com/leitor/136/edicao/641/ accessed 12-03-17.