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Sustainable Indicators for Resources and Energy in Building Construction

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ABSTRACT

Resources and energy indicators adapted to the building sector are developed in this study. Actually, sand and gravel seems to be abundant on Earth, but this is the accessibility to these resources that is scarce on a specific territory and these materials are not transported over long distances. In this study, different options to highlight this specificity are tested, and a new way of calculation the abiotic depletion indicator is presented, based on the ratio between importation and production of resources on a specific territory. Concerning the energy, it has been shown that the energy demand is redundant when added to global warming indicator. In this study, a dynamic approach is proposed which integrate a power comparison rather than an energy one. This method is applied to houses and permits to highlight the dependence at the different step of the life cycle of a building to high power energy sources.

INTRODUCTION

About 30 to 40% of the total natural resources used in industrial countries are exploited by building industries and about 30% of energy use is due to housing. This large consumption of resources and energy in the building sector has impacts on the environment. New sustainable development urges us to take into account the environmental aspects of building constructions. To achieve such sustainable management, political and economic decision-makers need indicators to quantify any technical choice dealing with resource consumption. Accurate indicators are needed, because any action is taken depending on the discrepancy between the desired state (or goal) and the perceived state of the system; and that the perceived state is approached with indicators. Meadows [1998] pointed out that it is impossible, for instance, to measure the exact population of fish in the ocean, but a way to approach this value is to measure the catch. Therefore, if an indicator of the state of the system is poorly chosen, inaccurately measured, delayed, noisy or biased, decisions based on it cannot be effective. On the contrary, with good indicators of sustainable development, it is almost impossible not to make decisions and take actions that improve indicators. For example, when a new US law required for each plant emitting toxic air pollutants to list these pollutants, an indicator was created, and local

newspapers began reporting the “top ten polluters”. Companies acted quickly to get off that list and toxic emissions decreased over 40% in 3 years, though there was no law against them.
This study focuses on the way to integrate resources and energy consumption into indicators adapted to the specificity of building products. As material resources and energy have their own specificity two different methods have been developed, but a common principle rules both methodologies. A strong distinction is made between a flow of matter or energy and an environmental indicator in which this flow is confronted to a reference. This type of indicator is defined as a state-pressure environmental indicator [Pulselli et al., 2007]. The objective of this study is then to develop state-pressure environmental indicators for energy and matter in the building construction sector. The hypothesis of this study is to state that for building construction sector, it is not the amount of energy or matter that is a pertinent indicator for sustainability, but when these quantities are related to time and space.

METHOD FOR ABIOTIC DEPLETION ASSESSMENT

Resource consumption indicators: a review

Resources can be divided into *biotic* resources such as biodiversity, sylvicultural products (wood, fish, etc.) and *abiotic* resources (that gathers all non biotic resources). Within abiotic resources, a distinction is often made between *mineral* resources, like metals; *bulk materials* such as sand, gravel or lime, and *energy* resources such as fossil fuels. Abiotic resource depletion is one of the most frequently discussed environmental impacts and there are consequently a wide variety of methods available for characterising contributions to it. A review of the different calculation methods for the abiotic depletion indicator is presented in Table 1.

Table 1. Methodologies to evaluate resource consumption: CML [Guinee, 2002], EDIP [Hauschild and Wenzel 1998], EcoIndicator 99 [Goedkoop and Spriensma 2001], and Impact2002+ [Jolliet et al., 2003].

Methodology		Indicator	Type of resource	Calculation
Mid-point methods	**CML 2001**	Abiotic depletion	energy, mineral	**Abiotic Depletion Potential:** $\frac{DR / R^2}{ref}$ *DR: Extraction Rate (kg.yr $^{-1}$)* *R: Ultimate reserve (kg)* *Ref: ADP of Antimony*
	EDIP	Resources	energy, mineral	**Flow (kg)**
End-point methods	**Eco 99**	Fossil fuels	energy	**MJ surplus / kg extracted** Increase of energy demand due to the lowering of ore grades
		Minerals	mineral	**MJ surplus / kg extracted** Increase of energy demand due to the lowering of ore grades
	Impact 2002+	Fossil fuels	energy	**MJ surplus / kg extracted** Increase of energy demand due to the lowering of ore grades
		Minerals	mineral	**MJ surplus / kg extracted** Increase of energy demand due to the lowering of ore grades

In most of the methods damage to abiotic resources integrates mineral resources and fossil fuels. Bulk resources such as sand or gravel are considered to be unlimited, which can be assumed at a global scale, where the stock for bulk resources is so important that it could be considered as infinite. But, as soon as the problem is focused on one territory, the concept of infinite reserve is wrong. Hence, as building materials are not transported over long distances, it seems more important to have a territory based approach to evaluate the availability of materials. In this study, the use of a Material Flow Assessment (MFA) to access to the potential reserve in a specific area that integrates the social metabolism of this area is therefore proposed.

Method for abiotic depletion assessment in a specific territory

Description of the method

To assess the potential resource stock of one territory, the temporal evolution of the ratio of two parameters calculated with MFA is used. *I* is the Import and *DMC* is the Domestic Material Consumption of the studied area. If the ratio I/DMC is increasing with time, it means that there exists an increasing difficulty to assess the resource. It is important to note that this *I/DMC* temporal trend is economic, social and geologic. The evolution of the importation compared to local production is not only linked to the natural depletion of the resource, but is also related to the specific economic context that can for instance facilitate importation rather than production. It is also related to social factors that can for instance limit opening of new quarries. However when the same trend can be observed for a long period of time, it can be assumed that this tendency is well implemented in the metabolism of the studied territory and that it will therefore continue for the next ten or twenty years except if a catastrophic event occurs (e.g. wars; global economic crisis). Therefore the resource depletion does not occur specifically for the natural environment but is more related to resource depletion in the anthroposystem, and the calculation of the potential reserve *R* on the territory (see table 1, CML method) is based on the assumption that no drastic change in the territory metabolism will occur. From there, *R* can be calculated with the following procedure:

1st step: Calculation of the amount of time until the exhaustion of the material, $t_{exhaust}$.

As the temporal evolution of the ratio *I/DMC* is known, the moment when resources will be exhausted is reached when this ratio is equal to 1. To calculate this date an extrapolation of data is needed. In this study, a linear regression is chosen, but different scenario for the future could have been chosen and the influence of this assumption is evaluated in Habert et al. [2009].

2nd step: Calculation of the potential reserve, *R*

R can be assessed by equation 1 which is the time integration of the evolution of the domestic production that can be expressed as the difference between *I* and *DMC*.

$$R = \int_{t_{actual}}^{t_{exhaust}} DMC(t).\left(1 - \frac{I}{DMC}(t)\right).dt \qquad (1)$$

The time integration is made between the present moment (t_{actual}) and the moment of resource exhaustion calculated in the first step.

The abiotic depletion indicator can then be calculated as described in table 1 for CML method with: *DMC* used for DR_i and R used for R_i. *DMC* is the current *DMC*, which therefore does not take into account the potential evolution in resource consumption.

Robustness of the method

This method uses a similar mode of thought as for the calculation of the ocean fish population. The stock is not measured, but a potential stock is assessed considering the way it is exploited over a long period of time. It is then submitted to large assumptions, on the temporal evolution of DMC and I, and one can question whether the tendency that is pointed out is a robust tendency or if it is sensitive to the observation time interval. The method to evaluate the validity of the tendency has been developed in previous study [Habert et al., 2009] and is synthesised here. The first step is to reduce the time window and to perform regressions for different time intervals. Actually, reducing the amount of data used to evaluate a regression will increase the variability between the different trends. From there the second step of the proposed methodology is to calculate the mean and the standard deviation of the linear regression parameters (slope and y-intercept) obtained for the different time intervals. For linear regressions on short time interval such as 3 year, a large variability is observed [Habert et al., 2009]. This variability then reduces when time interval becomes bigger. In order to choose the appropriate time interval for linear regression, the last step is to calculate the variance. It is proposed to choose the time interval where variance curve diminution reaches an asymptote. Once it is possible to have a mean trend of the *I/DMC* ratio evolution and variations around this trend (due to standard deviation use), it is possible to calculate a mean exhaustion time and also a minimum and a maximum exhaustion time. This will then permit to calculate a mean resources stock and extremes maximum and minimum stocks (equation 1). With this calculation, it is then possible to calculate the mean ADP indicator and variations along this value due to errors on stock evaluation. These errors are induced by the fact that the stock value this study aims to calculate is a potential accessible stock limited by many geologic, economic and social constraints; and that all these influences are assumed to be expressed in the *I/DMC* ratio evolution. It is assumed that at short time scale, the evolution of *I/DMC* ratio is related to punctual specific events, which could be compared very basically to short term erratic phenomenon on market stock exchange curves. At larger time scale a trend can be identified, and it is then necessary to chose the appropriate time scale to perform the regression that avoid erratic variations but still permits to evidence few variations in the main trend.

Results for bulk resources in France

Based on the available literature, the resources that are studied are aggregates at a country scale and then at a regional scale. For construction material depletion on the country scale, the tendency in the *I/DMC* variation is weak, leading to a mean slope close to zero **(Figure 1a)**. The uncertainty calculation method proposed in this study, allows us to assume a negative slope for *I/DMC* ratio of French construction materials **(Figure 2a)**. In this case the maximum exhaustion time has been considered as infinite, and we have then considered that, for the moment, with our calculation method, no evidences of any pressure on aggregates resource consumption can be observed on a country scale.

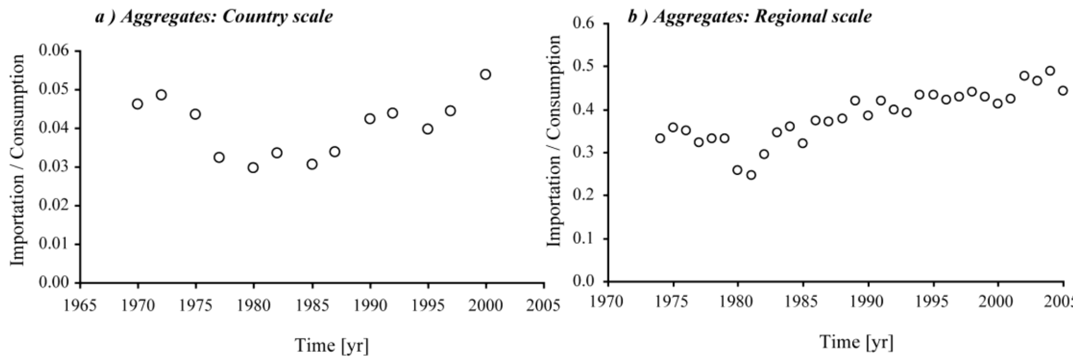

Fig. 1. Temporal evolution from France, for Importation/consumption ratio for aggregates a) at the country scale [sce: IFF, 2004], and b) at Ile de France area scale [sce: UNICEM, 1996; DRIRE, 1999; DRIRE, 2001; UNICEM, 2005]

In the Ile-de-France region scale, different studies have been used in order to have the evolution of consumption and production of aggregates from 1974 to 2005 [UNICEM, 1996; DRIRE, 1999; DRIRE, 2001; UNICEM, 2005]. The evolution of *I/DMC* has been plotted **(Figure 1b)**. The same methodology has been used: using a linear regression, the positive slope of *I/DMC* ratio evolution permits to calculate an exhaustion time with variations around this mean exhaustion time **(figure 2b)**. The abiotic depletion potential is then calculated **(Table 2)**. The potential abiotic depletion indicator is largely higher than for construction materials at the country scale. With this study, it is then possible to confirm that depending on the size of the studied territory the depletion of bulk resources is different. At a global world scale, depletion of bulk resources is negligible [Guinee et al., 2002; Van Oers et al., 2002], at a scale such as the French country, depletion is low and hard to evidence **(Figure 2a)**, and at a smaller scale, such as the IdF region, depletion is clear **(Figure 2b)**.

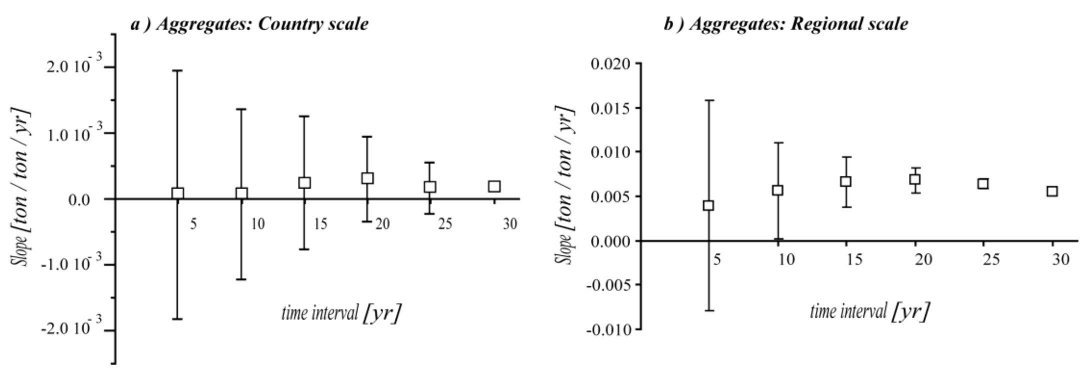

Fig. 2. Variation of the linear regression slope depending on the time interval used for regression for aggregates a) from France, and b) from Ile de France.

The methodology proposed here to calculate the potential stock of a specific material in a territory is based on an assumption. We assume that all processes that will influence the difficulty to use the local materials can be related with a single parameter; the temporal evolution of the *I/DMC* ratio. This can be justified if the potential stock that is calculated is not a geological stock of material in the territory, but a potentially accessible stock considering all the constraints from the anthroposystem. The preservation of the environment restricts new quarries opening. The social constraints such as the well known NIMBY (Not In My Back Yard) effect also limits quarries' activities due to noise, dust and visual pollution. Finally, the economic possibilities of the territory can facilitate importation rather than the higher cost required for local production. All these aspects contribute on a macro scale to the diminution of the use of local stock. In this study, it is assumed that all these constraints that limit the use of the local stock are finally equivalent to resource depletion.

Table 2: Abiotic depletion Potential for France and IdF

Localisation	Potential reserve [t]			extraction rate [t.yr^{-1}]	Abiotic Depletion Potential [kg Sb]		
	max	mean	min		low	mean	high
France	-4.56 10^{11}	5.56 10^{11}	1.65 10^{11}	4.08 10^{8}	-	4.59 10^{2}	5.20 10^{3}
Ile-de-France	6.72 10^{8}	4.82 10^{8}	3.60 10^{8}	1.53 10^{7}	1.20 10^{7}	2.33 10^{7}	4.18 10^{7}

One of the key points of this study is to evaluate resource depletion on a local appropriate spatial scale, but over a long time scale. Social and economic processes are considered to be erratic on short time scales and it is therefore necessary to evaluate processes on a larger scale to understand main tendencies. As a consequence, the proposed indicator is useful for long or medium term policies, since it is able to appreciate a potential depletion of resources considering a twenty years perspective. Actually, this time scale (20 years) is in the same order as the typical time scales of quarries opening (40 years) and of buildings life span (50 years). Then, it can be assumed, that the indicator is appropriate for building construction policies. Concerning the spatial scale, the abiotic depletion has been evaluated in this study on a country size scale and on a regional one. It is different from the usual abiotic depletion calculation which is performed at a world scale. One can then wonder whether these scales are appropriate or not for the purpose of the construction sector. The reasons of this choice are the same as for the time scale. Actually aggregates are materials that are transported over small distances, especially due to the price per ton transported, that doubles every 30 km. Resources policies are therefore envisioned on a regional scale, but maybe that a macro-region, such as the north of France would be more appropriate than an administrative distinction as used in this study in section 4.2. Calculations were not performed at this intermediate scale because of the lack of database on this scale.

As a conclusion, it seems necessary to perform multiscale calculation for this indicator which induce the production of 1) Material flow analysis of an area at different scale, as it has been done for instance for the Ile de France Region in Barles [2007a] and also 2) an historic evolution of the material flow at these scales. Historic studies of material flow evolution are often done at country scale [France: IFEN, 2008; Austria: Krausman et al., 2004] or city scale [Barles, 2007b] but do not often combine different scales.

METHOD FOR ENERGY CONSUMPTION INDICATOR

Once the resource use has been evaluated, the second important driver of sustainability is the energy.

Energy consumption indicators: a review

Many methods have been developed to evaluate the environmental impact of certain product's energy consumption. Each method highlights a certain aspect of energy. Emergy (spelled with a 'm') analysis quantifies the available solar energy previously used directly and indirectly in order to make a service or a product [Odum, 1996], exergy measures the potential work embodied in a material [Ayres et al., 1998] and the Cumulative Energy Demand (CED) quantifies the energy required during the life cycle of a product [Chapman, 1974]. CED is often associated to the Embodied energy. In the building sector all these indicators have been used. The Fossil CED has been shown to be closely linked to many other environmental impacts such as abiotic depletion or global warming [Huijbregts et al., 2006] and therefore give redundant information when they are used together as in common standardisation methods [AFNOR, 2004]. Embodied energy of building products is also closely linked to global warming potential indicator as it is evidenced in **figure 3**, which plot four different database which have collected greenhouse gas emissions (in equivalent CO_2) and energy demand (in MJ). As a consequence energy, as itself, do not give more information than using only Global Warming potential indicator. **Figure 3** shows that energy demand is closely linked to fossil fuel use which has been pointed out to be an important driver for the present climate change [IPCC, 2007]. In Europe, fossil fuel use also generates a dependency. Actually the European Union has been relatively fortunate over the period 1970-2000 with the exploitation of North Sea off-shore oil and natural gas. UK and Denmark provided indigenous fuels which permit to maintain a low import dependency (43%) [Hammond, 2007]. However by 2030, there will be a high importation (65-70%), which will obviously have serious implication for security of energy supply as consequent deterioration in the EU balance of payment and create political tension with Middle East countries and Russia [EU, 2002]. Even if coal is plentiful and available from a diverse range of geographical locations, it has a high carbon-ratio and it is therefore unlikely to be a fossil fuel of choice in an era of global climate change.

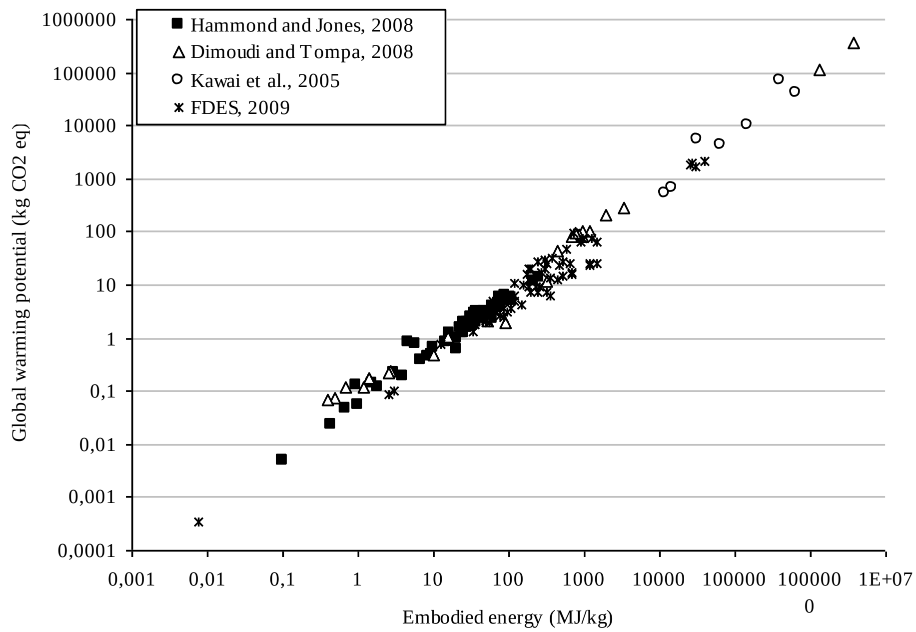

Fig. 3. Relation between the embodied energy and the global warming potential calculated by four different database for building product.

It is then commonly accepted that fossil fuel use has to be reduced, firstly to reduce CO_2 emission and secondly because of its depletion and the associated geopolitical tension that it will create. Many authors have then concluded that to reduce CO_2 emission and fossil fuel dependency, it is necessary to reduce our energy consumption. These considerations lead to energy savings programs and are currently driving many insulation optimisation and regulation in the building sector [Miguez et al., 2006].
But does the necessary reduction of fossil fuel use only means a reduction in energy consumption ? Are the CED, exergy or emergy indicators adapted to show pertinent ways of improvement for our societies?

Post carbon society and implication for energy use

Under these considerations, a few authors have proposed to evaluate the maximum amount of energy used in a low carbon society. Kesselring and Winter [1994] proposed the concept of a 2000 W society which aims at consuming not more than what correspond to an average continuous power of 2000 W per capita. The concept has been then further developed and applied by different authors [Pfeiffer et al., 2005; Schulz et al., 2008]. If these power considerations are put in perspectives with the distinction between flow and stock energies, one can show that a simple consideration of energy demand is not sufficient to lead societies towards a post-carbon era. Actually flow energies are energy types that go through the considered system, such as wind or sun radiation, which means that a certain amount of energy can be used during a certain period of time. In other words, the power is limited but not the amount of energy as soon as it is possible to wait. Contrarily, for stock energies, the power is unlimited, but the stock of energy is limited. Considering fossil fuels that are the main stock energies used, the stock is limited to the amount of fossil fuels that can be extracted. Furthermore, the reduction of the use of fossil fuel will probably be associated with an increasing use of renewable energies [Omer, 2008]. Hence the principal characteristic of post-carbon societies will be more probably power restriction, rather than energy depletion.

Energy consumption related to time

The hypothesis of this study is to state that for building construction sector, it is not the amount of energy that is a pertinent indicator for sustainability, but when this quantity is related to time. Therefore, in a resilience perspective it is important for an energy indicator to show the ability of a process to rely on renewable energies.

Proposed power indicator

It is proposed to calculate the power needed during the different step of the life cycle of a building rather than the energy demand. To calculate these powers two methods have been used i) a detailed study of the processes involved permit to know for each equipment parameters that allow to reach the effective power (For instance knowing the daily capacity and the energy needed to produce one ton) or ii) the power have been collected from bibliography. The results are gathered in table 3.

Table 3: Mean power of different equipments a) calculated, b) in bibliography.

a)	Energy (MJ/t)	Daily production (t)	Mean power (MW)	Ref
European Cement kiln	3 600	4 000	167	Bastier, 2000 and JCR, 2000
Blast furnace	12 726	4 107	605	Classen et al., 2007

b)	Unit (*)	Energy (MJ/*)	Mean Power (MW)	Ref
Loader (Caterpilar 950 F)	h	657,4	0,183	Martaud, 2008
Dragueline	h	484,4	0,135	Martaud, 2008
Jaw crusher (38-156 m3/h capacity)	h	475,5	0,132	Martaud, 2008
Spring cone crusher (PYD1750)	h	576,5	0,160	Martaud, 2008
Truck (20 t)	t.km	1,03	0,021	Kawai et al., 2005
Crawler excavator (0.6 m^3)	h	260	0,072	FNTP (JCB JS 180 LC AMS)

Once these powers are calculated, it has been chosen to calculate the power indicator for the system as the barymetric mean power depending on the amount of energy involved for each product. This barymetric mean power does not have a true physical meaning but from an environmental point of view it can be understood when comparing two solutions as the one who is the less dependant to high power processes. An application is given in the next session to compare three different building technologies.

Application for houses

The aim of the environmental assessment is to compare the production and operation phases of three houses made respectively in stone masonry, in rammed earth and in concrete. The details of the construction have been published by Morel at al. [2001] and the energy needed during the use of the houses have been given by the user and estimated at 4,547 kWh/yr for a service life of 50 years.

The results are presented in figure 4. Fig 4a represents the results for the current energy indicator. They confirm previous studies [Sartori and Hestness, 2007] that show that for conventionally built dwellings, the energy use for operation constitutes more than 80% in most case. Figure 4b shows the results for the power indicator proposed in this study. It permits to quantify the already known fact that conventional concrete house construction requires high power plants for cement and steel production. It highlights also that, the operation phase need very low power to meet the needs of a single house. Finally it has to be noted that even if houses built with local materials need far less power, they still need 50 to 100 MW, which is still very difficult to produce with renewable energies. Actually the main solar plant project in Europe has a power capacity of 20 MW (PS20 solar power tower, Sanlucar la Mayor, Spain).

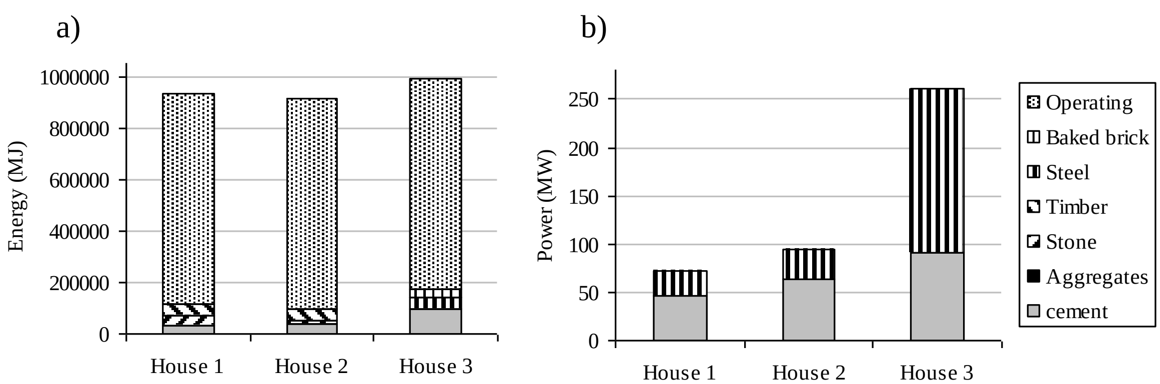

Fig. 4. a) Embodied energy and power indicators for houses 1) Stone masonry with soil mortar; 2) Stone masonry with soil mortar and rammed soil; 3) Concrete.

Energy consumption related to space

The act of building is not only an action performed during a certain period of time, it is also a process that is deeply rooted in a territory. An indicator of energy consumption could then be related to the territory where the building is made. This type of consideration could be done with the ecological footprint (EF), even if the surface calculated with the EF has nothing to compare with the actual territory as the area for fossil energy is the forest area required to absorb CO_2 emissions [Rees and Wackernagel, 1996]. The EF is more a way to represent a Material and Energy Flow Assessment, than a true land use indicator. In Life Cycle Assessent methods, Land use indicators are not correlated with energy demand [Huijbregts, 2006]. Two options can then be developed: The first one proposed by Huijbregts et al. [2006] would consider that as land use indicators and energy demand (CED) are not correlated, these two indicators could be used for sustainable indicators. The second one considers that in building constructions every process is related to the place where it takes place, and that the energy demand must then be considered in a territory based approach. This assumption has already been proposed by Pulsili et al. [2008] Who have calculated a ratio between local emergy and total emergy. However, the question is what kind of emergy can be considered as local? Pulsili et al. [2008] found that cement emergy had a ratio of local emergy higher than concrete, which does not have a pertinent signification. Further work on this aspect is therefore required, but a proposition could be to link the power needed to produce and use the house by the surface area that should be covered by renewable energy systems.

CONCLUSION

This article focused on sustainability in the building and construction sector. In this study different indicators have been developed for resources and energy use. The indicator of abiotic resources developed here shows local depletion of bulk resources. The depletion for sand and gravel can be seen on a regional scale but not on a national scale. As the appropriate scale for building construction is local, this indicator highlights depletions that could not be shown with previous indicators. For energy consumption, it has been shown that taking time into account underlines a different and significant dimension. Energy use has environmental concerns when it deals with the power needed during construction. It highlights the dependence on high power energy sources that are most of the time non renewable or CO_2 emitting products. This study is of course a very first assumption and much more work is needed

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