# Ecological Footprint at a Small Scale : Proposition of a Method and Model of Representation of Ecological Footprint for Industrial Activities

**Ibtissam El Bouazzaoui, Natacha Gondran and Jacques Bourgois**
ENS des Mines de Saint-Etienne, Sciences, Informations et technologies pour l'Environnement
158, cours Fauriel 42023 Saint Etienne cedex 2 - FRANCE
Email of corresponding authors : elbouazzaoui@emse.fr , Gondran@emse.fr , Bourgois@emse.fr
Telephone. +334 7742 0134 fax. + 33477426633

**ABSTRACT** Ecological footprint, proposes a kind of "ecological balance" that assesses and compares biologically productive area supply and demand. If the success of this index at a national level is proven, we assume that, to help each organisation or person to apprehend its own contribution to ecological footprint, it can be helpful to develop methods of estimation of ecological footprint at organisational level.

For a given sub national system two methods can be used to have an idea of its ecological footprint: (1) The national account based approach is based on the corrections of factors from the national averages of consumptions., (2) The component-based approach is based on an inventory of the consumptions and wastes generated by the observed system, the calculation of standards or specific transfer coefficients. This method seemed to the authors more appropriate. However, it requires several methodological adaptations to the classical ecological footprint methods and it presents some limitations.

In order to precise these adaptations requirements and limitations, we developed and experimented such a component-based approach on a real case. Our application field is a road work.

**Keywords:** environmental evaluation, ecological footprint, industrial activity, methodology , embodied energy

## Introduction

Since the beginning of the 90s, in France, evaluation is becoming a "necessary modality " of a " sustainable public action", according to the various reference texts that define the field and principles of sustainable development (Goxe et Rousseau, 2006).

Among the methods and instruments that were mobilized and experimented within the framework of environmental evaluation, the ecological footprint holds attention of various actors and notably of some local authorities (Boutaud, 2003).

## 1- Zoom on the general structure of the calculations of the Footprint

### 1-1- Definition

By the consumption of natural resources, the production and the use or of products and services, and the generation of wastes, human kind has an impact on the natural capital. Up to a certain point, the natural resources have the possibility to regenerate themselves. In theory they can satisfy our needs, as long as these last ones are not superior to the natural capacity of regeneration (biocapacity) (Wackernagel and Monfreda, 2003). Ecological footprint analysis makes possible the representation of biologically productive areas that are necessary to produce the resources that are consumed and wastes that are generated by a given population.
The classical method of ecological footprint calculation is based on the calculation of equivalence and yield factors thanks to national statistics of areas and tons of productions (Wackernagel et Ress, 1999)**.** Then, statistics of national consumptions (taken into account production, importations and exportations of products) are translated into global hectares representing global average biologically productive areas that are necessary to produce the resources that are consumed and the wastes that are generated by each population.
This method presents various interests by aiming to objective the representations of durability as well as the human demand on the global natural capital. On the other hand, we attribute him some disadvantages (Schaefer and al, 2006):
- The nature has no significant absorptive capacity for several important environmental problems: example the pollution by heavy metals, radioactive materials or persistent synthetic compounds. That means that substances without a significant absorption or regenerative capacity cannot be covered by the ‘Ecological Footprint/Biocapacity’ accounts.
- The analysis relies on having access to a reliable environmental database. But available statistics contain missing values, which call for some kind of imputation technique to estimate them. Often data gaps are filled under the use of a variety of different sources with different quality standards. So, the margin of error of EF/BC accounts based on shortcomings of the data sources is hard to quantify.

"The ecological footprint is a simple tool which gives a report of the human impacts (or the use of the ecological services) "(Chambers, Simmons et Wackernagel, 2000).
Some authors consider it as an indicator of durability : "the ecological footprint is an indicator of durability which expresses the relation between the consumption of a society and the natural environment" (Barrett, Cherret, Birch, 2004). It endeavours to express the level of overshoot of ecological capacity, within the present technological and social organisation conditions: if global demand exceeds global supply of biologically productive area, the well-being of the humanity will not be able to be maintained and development cannot be considered as “sustainable” (Boutaud, 2003).

Ecological footprint, at a national and global level, proposes a kind of “ecological balance” that assesses and compares biologically productive area supply and demand. (Wackernagel, 2005). If the success of this index at a national level is proven (living planet reports, for example), we assume that, to help each organisation or person to apprehend its own contribution to ecological footprint, it can be helpful to develop methods of estimation of ecological footprint at organisational level.

### 1-2- Two methods of calculation

The concept of the ecological footprint was launched at the beginning of 1990. During this decade, the method of the national calculations has been stabilized. On the other hand, to estimate ecological footprint at a local level (territory or organization), two methods can be used :

⌘ ***<u>The "national account based approach"</u>*** is based on national statistical data published by international organizations such as the FAO, for example. The missing data are collected among statistics issued from governmental, associative or academic organizations. For a local system, the use of *adjusting* factors allows the correction of the ecological footprint of the system that is studied according to its levels of consumption (below or above the average national consumption) for a chosen set of data.

**Principle of calculation of the National Account Based Approach**

As the objective of this article is not to re-describe in detail this approach (described in (Wackernagel and Monfreda,, 2005), for example), the principle of calculation is briefly commented.

The ecological footprint assumes that every (material and energy) consumption requires a certain quantity of bioproductive areas to support the movements of the resources and the absorption of the waste of this consumption.
To organize the data collection and allow its analysis, the ecological footprint method distributes the various surfaces according to two axes:

✓ **Categories of consumptions**
The consumptions are organized in five categories: food, accommodation, transportation, goods and services. This distribution allows to show the contribution of each category to the total ecological footprint.
The national annual consumptions (= production + importation – exportation) are inventoried and quantified, then they are converted in equivalent surfaces, by means of yield and equivalence factors (figure 1).

| | | | | | | |
|---|---|---|---|---|---|---|
| Consumption<br>(production + importation – exportation)<br>( t/year) | / | Yield factor<br>( t/ha/year) | * | Equivalence Factor<br>(gha/ha) | : | National Ecological Footprint<br>(gha/year) |

*Fig.1. Representation of the modalities of calculation of the national ecological footprint (according to Wackernagel and Monfreda, 2005)*

✓ **Bioproductive Areas**
The method of calculation of ecological footprint for nations distributes the ecological footprint according to six land type (Wackernagel and Rees, on 1999):
- Cropland: used to produce fruits, vegetables, cereal, etc.
- Permanent pasture: intended for the production of meat and dairy products;
- Forest: notably for the wood production;
- Marine: they cover 2/3 of the planet;
- Built-up: Unproductive area following the artificialisation by human constructions, erosion, etc.

-Energy (fossil fuel) : It is the necessary bioproductive area to absorb the CO2 freed by the combustion of fossil resources (oil, natural gas, coal), so that there is no increase of CO2 (hypothesis of climatic stability)[1]

⌘ ***The component-based approach or "bottom - up"***[2] (Lewan and Simmons, 2001) is based on an inventory of the various consumptions and wastes generated by the observed system, the calculation of standards or specific (when standard factors are not available) transfer coefficients. These factors can be based, for example, on life-cycle analysis studies.

### 1-3- Limits of the use of the " National Accounts " method for an industrial activity

For an organisation whose consumptions are very different from an average household, this method does not appear to be satisfying (Wackernagel, Monfreda, 2005). The national accounts method applies essentially to territories: countries, regions, cities, etc. Besides the problems that also arise for use in decision-making by local or regional authorities: lack of data and comparability of results (Wiedmann et al., 2006), the estimation of ecological footprint of an industrial activities presents specific problems. For example, the types of consumptions of an industrial activity are too different from national averages of consumption per capita to use adjusting factors. Specific factors, corresponding to specific consumptions must be calculated.

## 2- Objectives of a calculation of ecological footprint at the scale of an individual activity.

Our main assumption is that it is justifiable to try to adapt the method of calculation of footprint to the industry.
Indeed, Ecological footprint presents strong educational and communication interests. It can easily be understood by the general public and it presents an interest in term of arising environmental consciousness.
The results of the national ecological footprint reports[3] show that it is necessary, for developed countries, to reduce their ecological footprint. With this in mind, two levels of actions are necessary: act on the political, structural and economic organization of the society and encourage all the individual agents to reduce their footprint at the level of their organization and individual way of life. This second level of action will be facilitated if every individual actor can estimate, at the level of his organization (company, household, etc.) his own ecological footprint. So, companies could employ the ecological footprint to represent the impacts of their industrial activities on the natural capital. Indeed, this indicator could allow an organization to :

- follow the evolution over several years of its pressure on the natural capital and to measure the efficiency of the investments which are made for minimising these environmental impacts,
- identify, for a product or an activity, the distribution of the various pressures that are exercised on the natural capital,
- identify possibility of economy of consumptions of energy, water, and other natural resources,
- compare the environmental impacts between various industrial sites[4] or between several systems of production,

[1]The used rate conversion is : 1tC /ha /an [IPCC, 2001]
[2] Developed in the United Kingdom by Best Foot Forward : www.bestfoodforward.com
[3] See for example the Living Planet Report published every two years by the World –Wide Fund, the Global Footprint Network, UNEP Conservation Monitoring Centre on http://www.panda.org/livingplanet
[4] 'Sarl Empreinte Ecologique' in France, to refer to the web site : http://www.empreinteecologique.com/introduction_empreinte_eco.html

• inform in a synthetic and rigorous way on the environmental pressures that it exercises.

In the previous chapter, we approached two method for calculation of ecological footprint: The national account based approach and the component-based approach. This last one consists in modelling in a systematic way the observed system, by tracking its various streams of material and energy. The input data are based on a direct inventory of the consumptions. They can arise from dashboards of company or a specific inventory and assumptions (for the unavoidable lacking data). Then, these consumption data are multiplied by transfer coefficients , issued from scientific articles and data of LCA, in order to obtain a final result in global hectares.

This "component-based" approach is a method close to that of a life cycle assessment. It seems to us, more suited for calculations of footprint at the level of an organization.
However, it requires methodological adaptations to make more reliable the small-scale calculations. In particular, it requires developing a data base of transfer coefficients of the studied activities.
Such an adaptation arises methodological questions. In order to precise these adaptations requirements and limitations, we developed and experimented such a component-based approach on a real case. Our application field is a road work on the RN7 – RN 82 to turn a section into a 8 km four-lane road, between Cosne sur Loire and Balbigny in France This operation concerns a site of 50 hectares. This is a particularly complex case as it involves several participants (the Loire's departmental service for equipment is the prime contractor, the works are done by private companies) and is constituted by various very different phases of activity (earth-works, road way construction, etc.).

The first goal of this study is to complete an ecological footprint calculation in order to identify the type of conclusions that could be learnt from such studies as well as to recognize the specificities and limits of the method that we developed. The second goal is to propose a systematic framework of identification and follow-up of the various impacts that contribute to the ecological footprint of such an activity.

## 2-1- Methodological contribution for the calculation of footprint by the "component-based" approach: application to road works

### a. <u>Principle of calculation of the "component-based" approach</u>

The ecological footprint is assessed from a quantitative data collection from the direct inventory of the consumptions made on the studied site: mass [kg or t / year] or volume [m ³ / year] for the material, [kWh or GJ / year] for the energy. These values are converted at first into bioproductive areas, expressed in hectares/year, by means of a Conversion Factor (in ha / Unities of consumption) specific to each type of consumption and areas (Wernert, 2004). This area is then adjusted by means of the yield factors (FR) and Equivalence Factors (FE), to express an average global surface at the world level : the ecological footprint in gha.
The method of calculation is based on simple calculations that aim to multiply specific "consumptions" data for the studied site by generic data "transfer coefficients" (figure2).

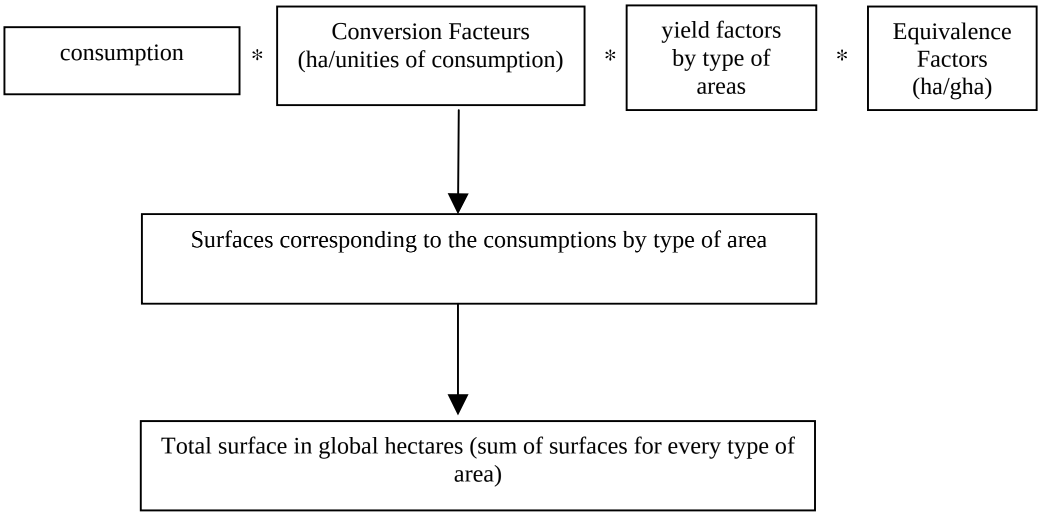


*Fig.2. Principle of calculation of the approach " component-based "*

**Followed methodology**

The methodology of calculation we propose consists of 5 stages:
- Definition of the perimeter of the studied system, to clarify to where we have to take into account the impact of the system and determine the limits of the consumptions which enter into the calculation.
- Inventory of the available data of consumption for the studied activity.
- Definition of the transfer coefficients corresponding to the collected data.
- Calculations of the footprints of the consumptions and addition of the various posts.
- Analysis of the results

- **Definition of the transfer coefficients**

The input data of the calculation are consumptions data. The output data are surfaces (global hectares). Transfer Coefficients allow the conversion of the collected data into surfaces. The transfer coefficients correspond to the type of data that were collected (types of material that are used, for example) on the studied site, but they are generic (based on scientific literature) and are supposed to be able to be used on several sites.
For the categories of consumption, several transfer coefficients were compared from various data bases on references in term of embodied energy[5] (mainly expressed there GJ / t or MJ / Kg) concerned of materials and emissions CO2. This comparison allowed us to bring to light the differences of hypotheses in the LCA. These differences can be explained by differences within the process of manufacturing of each material, but also by diverging assumptions that were made inside the life-cycle analysis. During this work, we were developed a non-exhaustive data-base of embodied energies corresponding to the materials susceptible to be met within the main categories of our studied activity: some examples are presented in table 1. The standards of ecological footprint calculations that advise to choose the weakest values (Global Footprint Network, 2006) when several assumptions can be made in order to enhance

[5] The energy that is embodied by a product, the good or the service, can be defined as the total energy required for its construction, since the extraction of raw materials until the assembly of by-products, by way of the intermediate phases of conversion, treatment, manufacturing, conditioning and transport of intermediary products and finished product. This approach is valid afterward for consumables, infrastructures, industrial plants and services.

the strength of the ecological footprint message (any contestation of the method can only contribute to increase the final footprint). Therefore, we choose the values of the weakest embodied energies to have a less important result of footprint.

The borders of the analysis of the embodied energies are rarely clearly defined within the literature. Besides, they are generally given without any indication of their level of uncertainty. Generally, the more a product undergoes of transformations before taking its definitive shape, the higher is embodied energy.

| | | **Carbon balance (ADEME , 2007)** | **Energy balance (embodied energy according to various LCA)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | LCA software Gabi4 | | data-base Negawatt[6] | | data-base Equer[7] | | data-base GFN | | (Maximum value - Minimum value)/ Average | |
| Material | Ceq Emissions factor (t eqC/t) | EF (gm2/ kg) | MJ/Kg | EF (gm2/ kg) | MJ/Kg | EF (gm2/ kg) | MJ/Kg | EF (gm2/ kg) | MJ/Kg | EF (gm2/ kg) | MJ/Kg | EF (gm2/ kg) |
| Paper | 0,55 | 5,3 | 16,5 | 1,3 | 36,4 | 2,9 | - | - | 35 | 2,8 | 0,68 | 1,3 |
| Concrete | 0,055 | 0,5 | - | - | - | - | - | - | 1,5 | 0,1 | | |
| PVC | 0,51 | 5,1 | 16,7 | 1,3 | 70 | 5,6 | 75 | 6 | - | - | 1,08 | 1,4 |
| Copper | 0.80 | 7,8 | 36,7 | 2,9 | 70,6 | 5,6 | 125 | 10 | - | - | 1,13 | 1,08 |

*Table.1.Examples of embodied energies of some materials according to various sources*

- **Examples of calculation of transfer coefficients and possible methods**

### *Calculation of 'CO$_2$ areas' footprint*

The standard ecological footprint calculation method considers that the footprint that is associated to the direct or indirect energy consumption corresponds to the surface of forest that is necessary to absorb the emitted CO2 and which is not absorbed by the oceans. By hypothesis, the produced energy results from the combustion of fossil resources, except particular cases like hydroelectricity that can be calculated differently. The calculations rely on the characteristic values of oil that is considered as "average" fuel compared to the intensity of emission of CO2 towards the other fossils fuels (coal and natural gas).

The ecological footprint which translates the energy consumption is expressed in term of surface of $CO_2$ areas. The conversion Factor between the consumed energy and the surface of forest, is called the carbon sequestration factor. It is expressed in m ² of forest by ton $CO2_{equivalent}$. He can be calculated for each type of fossil energy (m2/MJ) according to the emissions of carbon of these various fossil fuels. The general formula for this calculation is the following one :

[6] http://www.negawatt.org (consulted in 2004)
[7] http://www.izuba.fr/equer.htm (consulted in 2005)

Carbon Sequestration Factor [m2/MJ]= Carbon emission intensity[tC/GJ]/ 1000[MJ/GJ] * (1-fraction absorbed by ocean)/ Sequestration Rate [tC/ha] * 10 000 [ha/m2]

*Equation 1: carbon Sequestration factor by forests for the combustion of fossil fuels*

The oil presents an intensity of emission of carbon equal to 0,02 tC / GJ (HEFC RP, on 2003). Based on IPCC data, the Global Footprint Network considers that 29 % of the emitted carbon is stored by the oceans (national calculations, GFN, 2001).On the same IPCC basis, it also assumes that one hectare of average forest can accumulate approximately 1 ton of carbon a year (IPCC, on 2001). Thus, the Carbon sequestration factor for the use of oil is 0,14 $m^2$ / MJ. The equivalence factor of '$CO_2$ areas' is equal to that of ' forest area ', i.e. 1,38 gm2 / m2. Generally, the equivalence [EF] factors are identical for all the countries for definite year (Wackernagel and Monfreda, 2005) and the yield [YF] factors are variable from a country to a country for definite year.

Ecological footprint for $CO_2$ areas [gha] = area necessary for the carbon sequestration [m2] * EF [gm2/m2]* YF /10000[gm2/gha]

*Equation 2: ecological footprint ' energy (fossil fuel)' expressed from an energy balance*

Therefore, the global carbon sequestration factor is 0,19 $gm^2$ / MJ.

Two methods are possible to determine the "energy" footprint that is associated to energy consumption: *energy balance or carbon balance.*

**Energy balance method**: This assessment is based on a value of embodied energy by mass, expressed in gigajoules by ton (or MJ / Kg) of each materials that are used. It implies to know approximately the quantity of material that is inside the various products that are used. Thus, this value can be multiplied by the consumption of the material that is considered, then by the carbon sequestration factor for oil, to obtain a global surface.

$CO_2$ areas [gha] = Consumption [kg]* embodied energy (MJ/Kg]* carbon sequestration Factor [m2/MJ]*Equivalence Factor [gm2/m2]* Yield Factor /10000[gm2/gha]

*Equation 3: Surface of ' energy (fossil fuel)' expressed from an energy balance*

**Carbon balance method:**

This method is based on values of Carbon equivalent emission, expressed in ton of Ceq by ton of product[8]. Thanks to the rate of absorption of forests, the corresponding surface can be obtained. This surface is then multiplied by the equivalence factor [gm ²/m ²] which allows to transform hectares into global hectares, as it is indicated in Equation 4:

[8] The factors of emission used generally arise from the Carbon balance method of the ADEME, France (ADEME, 2007)

$CO_2$ areas Ecological footprint [gha] = Consumption [t] * Emission factor [tC/t] * (1- fraction absorbed by ocean) / Sequestration Rate [tC/ha] * EF [gm2/m2]

*Equation 4:* $CO_2$ areas *ecological footprint expressed from a 'carbon balance method'*

**b. Application in the road of 'Vendranges'**

**• Definition of the perimeter**

The first phase of the study consists in defining the perimeter, which is the border of the studied system: activity under study, period on which the data are collected.
We choose to limit our study to the phases of " general excavations " and "pavement phase" to calculate the ecological footprint of the road works of Vendranges, This choice was made because of the availability of data only for these phases and because of their strong responsibility within the total footprint of the road works.
Our calculation of the ecological footprint is thus an estimation of the impact on natural resources of road works on the global environment. Our main objective is methodological. Indeed, the environmental impacts of such a roadwork vary considerably according to the characteristic of the site and the chosen techniques of construction.
Road works are seen as an entity, which uses a certain surface of productive area that is necessary to supply the resources that are consumed, and to assimilate the wastes which it generates and which are reintroduced in the natural environment. The main elements that are taken into account within the analysis are the surfaces that are mobilized for the construction of the road, the consumables, infrastructures and industrial machines that are used in this activity.
Certain elements are not taken into account due to the lack of data: for example, the fuel that was used to transport consumables that were used on the site (Explosives, fuel used by machines, materials used by asphalt station platform). Also, the transportation of employees and materials were not taken into account for the excavations phase. For the pavement phase, the ecological footprint of the transportation of employees, of building materials and fuel (for the machines and the asphalt station platform) were taken into account.

**• Inventory of the data of consumption**

The first condition for the footprint's calculation is to access to a rather precise qualitative and quantitative knowledge about the consumption and waste of the studied site. For the present study, some of these data arise from the environmental analysis of the road (CESAME, 2004); the others were obtained from the Transports and Infrastructures service of the DDE of the Loire, which is in charge of the operation, as well as its subcontractors (the " FOREZIENNE " and "MALET" companies).

***Adaptation of the consumption categories***

In order to simplify the data collection and to detail the ecological footprint, the five following consumption categories have been defined:
- Consumables (which replaces the food category): For example: water, fuel used on the road works, concrete for sanitization pipes, explosives, etc.
- Infrastructures (instead of the shelter category): For example: offices, networks, energy, etc.
- Mobility (during the pavement phase): transport of employees and agents, but we also included in this phase the transport of building materials (whereas only the transport of persons is considered in the traditional footprint standards)
- Goods and equipments: For example: construction machines.

- Services: For example: waste water treatment of the offices or telephone service.

***The various land types to be considered***

The land types of our study are consistent with the National Footprint Accounts:
- $CO_2$ areas correspond to the area of forests that is necessary to absorb the CO2 that is directly emitted by the activity, and indirectly throughout the life cycle of consumables.
- Built-up areas: are lands that became biologically unproductive, either because they have been covered for the human needs, or because they have been exploited in extraction activities (mines, careers, etc.), or because they have been contaminated by pollutants which alter the productivity (Wackernagel, 2005). In the case of a road , the following elements were taken in account: the road right-of-way, the necessary surface for the clearing/ballast storage as well as for the temporary installation of offices and the necessary surface for the production of certain materials produced outside of the local road-works (example of the concrete).
- Forests: Theses areas correspond to the wooden production (for the manufacturing of the paper).

As fishing grounds did not seem relevant to the studied activity (because of the lack of fish consumption !), we proposed a new land type more adapted to this activity:
- The Aquatic areas that takes into account the ecological footprint associated with the consumption of water on the construction site, and the impact of the roadworks on the rivers and water resources. The following types of water consumptions were taken into account: sanitary drinking water, water in bottle, non-drinking water for track watering and the quantity of water used to make certain construction materials, notably concrete, for sanitization pipes and the installation of cast iron gutters.
- In the case of roadworks, the contribution of footprint on cropland and grazing areas is considered as immaterial because the consumptions of farm produces (employee's alimentation) have not been taken in account.

- **Examples of calculations**

***→ Example of the footprint of the 'consumables' category: example of fuel, concrete and paper.***

*** Ecological footprint of Fuel use**

***Appropriation of $CO_2$ areas***

The ecological footprint takes into account the main fuel consumptions (direct use of fuel by construction machines and asphalt station platform). Both calculation methods of the footprint due to the energy consumptions (energy and carbon balances) are applied for the calculation of footprint of the fuel.
The energy balance method is based on a value of embodied energy of diesel. This embodied energy value is multiplied by the diesel consumption on the construction site, then by the carbon sequestration factor for the oil, in order to obtain a surface.
Its conversion to global surface is done by the multiplication by the yield and equivalence factors as explained in equations 2 and 3 (equation 5).

Surface of $CO_2$ area $_{fuel}$ [m2] = Consumption [L]* Density of the diesel [kg/L]* diesel embodied energy (MJ/Kg]* Carbon sequestration Factor for the Oil [m2/MJ]

*Equation 5.a : Surface of $CO_2$ areas $_{fuel}$ expressed from an energy balance*

Ecological Footprint$_{carburant}$ [gha] = Surface of $CO_2$ area $_{fuel}$ [m2] * Equivalence Factor [gm2/m2]* Yield Factor /10000[gm2/gha]

*Equation 5 .b : $CO_2$ areas ecological footprint for the fuel*

The $CO_2$ areas footprint of fuel, by the carbon balance method, is calculated from the equation 4, by considering the value of $CO_2$ emission factor (ADEME, 2007): 0,95 tons of C by ton of diesel.

The built-up area related to fuel extraction and refining has been considered as immaterial with relation to the appropriation of $CO_2$ area.

This approach is consistent with the National Footprint calculations. However, it presents the disadvantage not to take into account any other impact of fuel combustion except global change (for example, local pollution, environmental impacts of the fuel extraction, etc.).

*** Ecological footprint of Concrete use**

***Appropriation of $CO_2$ areas***

Energy balance method: the quantity of concrete of the sanitization pipes which have been installed during the excavations, as well as the quantity of concrete which have been used during the embankment phase (for the installation of trenches for example): 5168 tons.
A value of embodied energy of 1.2 GJ by ton of concrete was chosen (Chappat and Bilal, on 2003) in order to apply afterward the equations 2 and 3 for the calculation of energy footprint of the concrete that has been used on the construction site.

Carbon balance method: the tonnage of concrete is directly translated into energy footprint, from the equation 4 by considering the value of emission factor (ADEME, 2007): 0,055 tons of C by ton of concrete.

***Appropriation of built-up areas***

The main materials consumed for the road building are aggregates, concrete (sanitization pipes for example) and the asphalt.
Due to the lack of precise data on the production of these materials, only the footprint in built-up areas for the concrete has been considered. For that purpose, the number of degraded hectares for producing one ton of concrete has been estimated.
About 400 Mt of aggregates is produced in France (IFEN, 2006). On average, we consider[9] that it requires degraded 57 143 hectares: 7000 t / ha.
The various sorts of aggregates in France (UNICEM[10], 2004) are distributed there:
118 Mt of eruptive rock (approximately 16 857 ha)
105 Mt of calcareous rock (approximately 15 000 ha)
142 Mt of alluvium (approximately 20 285 ha)
20 Mt of sands (approximately 2 857 ha)
6 Mt of marine aggregates (approximately 857 ha)
Considering hectares degraded to produce these various types of aggregates and taking into account the quantities of main necessary[11] aggregates to produce one ton of concrete, we

[9] these estimation are based on former figures found in the work " The industry of careers and sustainable development ".
[10] Conference MESH-MALO (November 8th and 9th, 2005)

obtain a value about 0,0013 ha / ton of concrete. Let us again note that this estimation does not take into account the impact on the environment of the quarries.

*** Paper**

***Appropriation of $CO_2$ areas***

Energy balance method: The tonnage of paper that has been used in the offices for these road works. Equation 3 is then used to calculate energy footprint of the paper.

Carbon balance method: The energy footprint of the paper is calculated from equation 4, by considering the value of $CO_2$ emission factor (ADEME, 2007): 0.55 tons of Ceq by ton of paper.

Let us note that this footprint does not take into account the exploitation conditions of the forest useful for the paper production. It also neglects the area necessary to the papermaking process.

***Appropriation of forest areas: calculations of necessary surface of forest areas for the extraction of the pulp for paper production (paper of offices)***

The calculation of surface of forest areas for the wooden production rests, in our case, on the quantity of wood that has been used for paper production. There are two methodologies:

- The first one consists of calculating the footprint of the paper according to the yield of French forests. This choice, which has been adopted, gives the weakest result of footprint. In fact, it is supposed that the paper that is consumed during the building is produced from wood exclusively issued from French forests. For this calculation, the following parameters have been used: the yield of French forests equal to 5,33 m3 of wood per hectare, the wooden tonnage for one ton of paper equal to 1,11[12], the density averages of wood and the yield Factor of forests areas for France (equation 6):

Surface of forest areas [gha] = paper Consumption [t] / yield [m3 of wood/ ha] * tonnage of wood for one ton of paper[t wood/t paper] / Density of the wood [t bois/m3 bois] * Equivalence Facteur of forest area [gm2/m2]*Yiel Facteur of forest area for France

*Equation 6: Forests areas of the paper*

- The second one consists of calculating from the world global average yield of forests . This choice could be adopted if we do not know exactly the origin of paper. The same reasoning of the equation 6 is applied for this calculation by considering the global average yield of 1,51 $m^3$ of wood per hectare (GFN) and the yield Factor of forests areas all over the world.

**→ *The example of the footprint of the ' equipments ' category: the example of machines used on the road-work***

***Appropriation of $CO_2$ areas***

Energy balance Method: the road building requires the use of various equipments. Tonnages can be obtained, thanks to the data of the manufacturers, concerning the various machines used during the construction process (total of 2096 t) : Shovels, bulldozers, articulated

---

[11] http://www.ciments-calcia.fr et www.creargos.com

[12] http://cerig.efpg.inpg/lgc/dossiers/papier

autodriving tipcart, stiff autodriving tipcart, graders, wagon of drilling, compactor, machines under treating, etc. This number is then divided by the average life of these machines, by considering that every machine has been used during approximately one year on the construction site (and that every machine will certainly be used somewhere else after this road building).
then, this value is multiplied by the embodied energy (assuming 100 GJ by ton of industrial machine (GFN)), then by the carbon sequestration factor for the oil and then by the yield and equivalence factors:

$CO_2$ area Ecological footprint $_{\text{industrial equipment}}$ [gha] = Consumption [kg] / Life expectancy averages equipments * Industrial equipment embodied energy (MJ/Kg] * Carbon sequestration Factor of oil [m2/MJ]* Equivalence Factor [gm2/m2]$_{CO2\ area}$* Yield Factor /10000[gm2/gha]

Carbon balance Method: we chose the emissions factors of (ADEME, 2007), for the main materials used for the manufacturing of a vehicle of one ton (plastic, aluminium, glass, steel, rubber, liquids, electronic materials). These factors can be translated directly into surface by $CO_2$ areas to calculate the footprint of a vehicle of a ton. Afterward, the obtained result (the footprint of a vehicle of a ton) was multiplied by the total tonnage of machines used on the construction site, divided by the average life expectancy of machines.

***→ The example of the footprint of the 'Services' category: the example of Wastewater Treatment of the living-base buildings (offices)***

***Appropriation of built-up areas***

To determine the footprint of built-up areas of wastewater, we propose to estimate the built hectares corresponding to 1m3 of wastewater.
We thus consider that wastewater living-base is completely treated in water-treatment Station by lagooning. We refer to the parameters related to a station of 250 000 m3 per year of capacity and which extends over 7 hectares[13]. Let be an average of 0,000028 ha per m3 of wastewater treated by lagooning. These hectares are then multiplied by the yield and the two equivalence factors.

## Zoom on the main results

The first step was to calculate the partial footprints for each consumption category for each stage of roadworks (earthwoks, asphalt paving), we add the various posts of both stages to obtain the total footprint (table 2 ). This result does not include certain data either because they were difficult to find and to estimate (example of the transport of the phase excavation), or due to the lack of certain transfers coefficients (explosives for example). So, this lack of availability of certain data reduces the result of footprint of the roadworks.

[13] www.enseeiht.fr (Example of the lagooning station of " Casie ", France)

| | EF (gha) General excavations | | EF (gha) asphalt paving | | Total Footprint (gha) | | |
|---|---|---|---|---|---|---|---|
| Consumption category | Energy balance | Carbon balance | Energy balance | Carbon balance | Energy balance | Carbon balance | **Difference between energy and carbon balance method** |
| Consumables | 1828 | 2003 | 1409 | 1021 | 3238 | 3024 | 7 % |
| Infrastructures | 132 | 122 | 116 | 123 | 247 | 245 | 1 % |
| Mobility | _ | _ | _ | 110 | _ | 110 | _ |
| Goods and equipments | 233 | 183 | 143 | 59 | 376 | 242 | 36 % |
| Services | 0 | _ | 0 | _ | 0 | _ | _ |
| **Total** | 2193 | 2308 | 1668 | 1313 | **3861** | **3621** | **6 %** |

*Table.2. Distribution of the ecological footprint of the road 'Vendranges' according to various consumptions categories and the stages of roadworks*

A difference is observed between the two methods that we used to evaluate the $CO_2$ area (Energy balance and Carbon balance). This can be explained by the differences on the transfer coefficients that were chosen according to the source (specific LCA or carbon balance (ADEME, 2007). We also noticed that, when several life-cycle analysis were available, their results could largely differ. These differences can be explained by differences within the LCA assumptions but also to real differences according to the process of manufacturing of every material that were studied (table1).
Following Global Footprint standards (Global Footprint Network, 2006), when several hypotheses were possible, we choose the option that gives the weakest result of footprint in order to give more weight to the final result (the result is a minimal figure which under respect the reality).

If we observe the distribution of contributions in the total ecological footprint of the construction of the road according to the various spending categories, we find that the ecological footprint is mainly due to the consumables category (essentially, fuel and building materials " concrete, aggregates, asphalt ") (Fig 3).

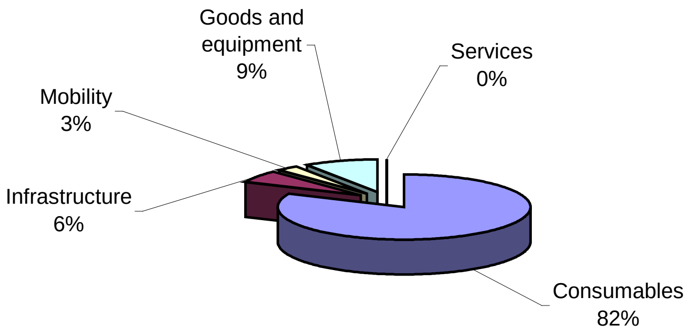


*Fig. 3. Distribution of the ecological footprint according to the various categories of consumption of the road of Vendranges during the phase of construction (general excavations and asphalt paving stages)*

The results obtained from the footprints estimation of the category ‘consumables’ at the level of the studied road during both stages of construction, show that theb main ecological footprint is exerced on the $CO_2$ area land type ( Fig 4 ):
These energy consumptions are the consequence of the large quantity of fuel and materials (generally the products of career) used on the road works.

Fuel consumptions are placed within the "consumables" category because they concern both the necessary energy to extract the excavated material, to crush and transport these materials to build and stabilize the road embankments and to the unavoidable storage zones.

The quantity of fuel consumed by the asphalt station platform is added. The information on the used quantity of fuel for the transport of materials was not available comparing to the construction activity.

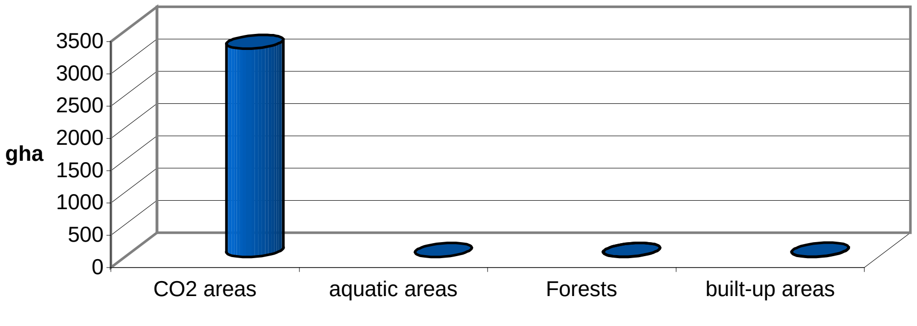


*Fig.4. Distribution of the partial footprint of the consumables category, the road in phase of construction (general excavations and pavement phase), areas according to the various land types*

Our study put in evidence the respective impacts of certain consumptions that may have been able a priori neglected such as the embodied energy of construction machines used on the road (The footprint of the goods and equipment category on $CO_2$ areas amounts to 30 gha /km). It is due to the important number of machines used for these road works in phase of construction.

## <u>Conclusion</u>:

This study confirms that the component-based approach is very close to a life cycle assessment although its processing may be simpler and faster as it considers a smaller number of impacts. Ecological footprint computations are based on modelling, in a systematic way, the object of study in order to describe the various fluxes of material and energy. It can be applied to various activities.
As it takes into account all the detailed data of the perimeter of study, the component-based approach gives the closest result to the reality. However, a combination of both methods can sometimes be necessary. This approach is named Stepwise method (Alberdi, 2006). It consists in using a **component-based approach** when the local data exist and **a national account based approach** otherwise. The two approaches are then complementary (RPA, DEFRA, 2005).

Our main results of footprint computation for these road works is the fact that certain consumptions that would have been able to be a priori perceived as unimportant (bound to the energy and the material necessary for the manufacturing of the machines of construction site and the sanitization pipes for example) present some important impacts. Beside this, one of the main advantages of the ecological footprint is to integrate some other factors than the $CO_2$ emitted throughout the life cycle of the considered product. For example, the surface that is necessary for the production of the wood used for the paper as well as the surface necessary for the production of building materials (the concrete for example) or for the water treatment can be taken into account.
In addition to this, thanks to this work, two methods that can proposed for footprint estimation were compared.

This study showed that this tool could be used as a global environmental impacts management chart in order to track the main consumptions and global impacts of an activity (the case of the studied road). The footprint in that case of study could give a systematic framework to the follow-up of energy consumptions, consumables, goods and services.

However, certain methodological limits can be observed from the use of ecological footprint at the level of an organization or of an activity:
- The unavailability of certain data must be underlined(example of the embodied energy of explosives) or consumption data of the activity (data on employees transportation for example).The cost related to the acquisition of such data (time needed) may be important.
- The data of ecological footprint are given, at this moment, without any indication on their level of uncertainty. This can be explained by the fact that for national calculations, the statistics are diffused without indication of any uncertainty (Wackernagel and Monfreda, 2004). The knowledge of the levels of uncertainty related to the transfer coefficients (for example, embodied energies are given without any indication onto their level of uncertainty) and the collected data could make a first contribution to the estimation of the level of uncertainty of ecological footprint, which is especially used in a qualitative way and in communicative purpose. If it isused as decision-making tool, a reflection on its sensibility and uncertainty turns out necessary.
- Without ignoring the variability on the conversion factors according to chosen sources (table 1), the application of several methods for the calculation of footprint of certain consumption

categories gives variations between 1 % and 36 % between the results of footprint of these consumption categories (for example, Energy Balance method and Carbon Balance method, table 2). But, one of the basic principles of the calculations of ecological footprint, when several hypotheses appear, is to choose the option which gives the weakest result of footprint in order to give more strength to the message (Wackernagel, 2005): " we estimate the minimal ecological footprint of the organization in question ".

- In theory and from national calculations, the component-based approach supplies more precise and detailed results than the National-account based approach (with adjusting factors). However, this precision is limited because the available number of conversion coefficients are limited and the missing coefficients are mostly calculated by considering essentially (but not only) the energy constituent of the footprint and thus its $CO_2$ area.
- There does not exist any " standard " and official databases about the embodied energy and the environmental impacts of the various materials. This problem, which is also present within LCA or carbon balance analysis, makes difficult the comparison between different studies. In addition to this, the results vary according to the assumptions that are made. this makes necessary the creation, for each new study, of a database of the conversion factors (example of embodied energies) of the materials that are involved. Within our study, we choose to confront various sources within this database to evaluate the variations between the results (some examples are presented in the table 1).

The embodied energies for the same material vary with the various possible circuits of production. According to countries and processes that are involved, these embodied energies and thus the conversion factors can strongly vary, which leads to difficult comparisons between various systems. Thus, it can be questioned whether it is preferable to build a common and international database of conversion factors or to rebuild appropriate databases for each country and even for each system under study, in order to take into account the disparities at the level of the circuits of production and distribution.

- The determination of the ecological footprint of the fossil energy, which only takes into account the necessary surface to absorb the CO2 in surplus, leaves aside numerous greenhouse gases and other pollutants and considers that the same forest area cannot fill functions of absorption of greenhouse gases and wooden production.
- We make the hypothesis that 1/3 of the CO2 is absorbed by the ocean, but this 1/3 may turn to 0 in a long period of time because of the possibility of the biosphere saturation with regard to its absorption capacities (Canadell, Pataki, on 2007). In this case, the $CO_2$ footprint will be much higher.
- Toxicological aspects and the use of the nuclear energy are not taken into account in a satisfactory way: the nuclear energy is counted for example in the same way as the fossil fuels while the effects of these two fuel sources are very different. Wackernagel and al. (2005) recognize this weakness and defend the idea that it is impossible to quantify the effects of the radioactive waste in terms of surface because areas have a capacity of assimilation almost null. Instead of deciding not to count this energy, they prefer to consider it as the fossil energy.

**Definitions :**

* **Biocapacity**: is the counterpart of the Footprint, or the offer side. A nation's total Biocapacity is the sum of its bioproductive areas, also expressed in global hectares (gha). Each bioproductive area is transformed into global hectares by multiplying its area by the appropriate equivalence factor and the yield factor specific to that country (Wackernagel and al, 2005).

***Transfer Coefficient**: is the product of the conversion, yield and equivalence Factors. This coefficient is specific in every article of consumption and waste, and allows to convert directly the data of inventory of consumption in global hectares of ecological footprint.

* **Conversion Factor**: factor allowing to convert the consumptions on-surface of productive areas, the considered country.

* **Equivalence Factor**: represents the world's average potential productivity of a given bioproductive area relative to the world average potential productivity of all bioproductive areas. Cropland, for example, is more productive than pasture, and so has a larger equivalence factor than pasture.

* **Yield Factor:** describes the extent to which a biologically productive area in a given country is more (or less) productive than the global average of the same bioproductive area. Each country has its own set of yield factors, one for each type of bioproductive area. Each year the yield factor is calculated anew. Specifically, the yield factor is the ratio between the area a country uses in the production of all goods in a given category calculated with national yields, and the area that would be required to produce the same goods with world average yields.

## References

ADEME. 2007. Bilan carbone 2007 . Disponible in : < http://www2.ademe.fr>

Alberdi L. 2006. L'empreinte écologique des zones urbaines. Estimation de l'empreinte du canton de Genève : rapport de stage de DES. Diplôme d'études supérieures en études urbaines. Université de Genève/ Université de Lausanne, 2006, 58p.

BARRETT J, CHERRET N, BIRCH R. 2004a. Step Change: An Analysis of the Policyand Educational Application of the Ecological Footprint. Rapport pour WWF daté de mars 2004.

Barrett J, Vallack H, Jones A, Haq G. 2002. A Material Flow Analysis and Ecological Footprint of York, Technical Report. Stockholm Environment Insitute, 2002, 129p.

Boutaud A. 2003. Développement durable : à la recherche des bons indicateurs, problèmes économiques n. 2800, mars 2003, pp. 1-3.

Canadell JG, Pataki D, Pitelka L. 2007. Terrestrial Ecosystems in a Changing World. The IGBP Series, Springer-Verlag, Berlin Heidelberg.

CESAME. 2004. Analyse environnementale du chantier de Vendranges RN7-RN82. Etude réalisée pour le compte de la DDE 42. 57 p.

CHAMBERS N, SIMMONS C, WACKERNAGEL M. 2000. Sharing Nature's Interest : Ecological Footprints as an indicator of Sustainability. Earthscan, London.

Chappat M, Bilal J. 2003. La Route Écologique du Futur, Analyse du Cycle de Vie, Consommation d'énergie et émission de gaz à effet de serre. Colas, 2003, 34 p.

Global Footprint Network. 2006. Ecological Footprint Standards 2006. Disponible in : < www.footprintnetwork.org>

Goxe A, Rousseau S. 2006. L'empreinte écologique : Nouvel indicateur, ancienne approche? Mise en perspective et analyse territoriale de l'empreinte écologique. In : Les indicateurs territoriaux de développement durable. Paris : L'Harmattan, 2006.- p139-155.

HEFC RP. 2003. Household Ecological Footprint Calculator v3.2. Oakland : Redefining Progress, 2003. Disponible in : < http://www.rprogress.org > (consulted in 2004).

IFEN. 2006. Les impacts du réseau routier sur l'environnement. IFEN, 2006. Disponible in< http://www.ifen.fr>

INSEE. 2003. CHARPIN J.-M. Annuaire statistique de la France, édition 2003. INSEE - Statistique Publique, 2003, 586 p.

IPCC. 2001. Climate Change 2001 : the Scientific Basis. Cambridge, UK, Cambridge University Press, Intergovernmental Panel on Climate Change (IPCC).

Lascoumes P. 2005, « Le développement durable, vecteur d'innovations politiques ? », in Smouts M-C. (ed.), Le développement durable : les termes du débat, Paris, Armand Colin, pp. 95-108.

Lewan., Simmons. 2001. The use of Ecological Footprint and Biocapacity Analyses as Sustainability Indicators for Subnational Geographical Areas : A Recommended Way Forward. European Common Indicators Project, EUROCITIES / Ambiente Italia, 2001, 24p.

RPA, DEFRA. 2005. Sustainable Consumption and Production – Development of an Evidence Base. Study of Ecological Footprinting. Final Report.
http://www.defra.gov.uk/environment/business/scp/pdf/footprint-final.pdf

Schaefer F, Luksch U, Steinbach N and al. 2006. Ecological Footprint and Biocapacity. The world's ability to regenerate resources and absorb waste in a limited time period, 11p.

Wackernagel M, Monfreda C, Moran D, Wermer P, Goldfinger S, Deumling D, Murray M. 2005. National Footprint and Biocapacity Accounts 2005: The underlying calculation method. Global Footprint Network, Oakland, CA.

Wackernagel M, Monfreda C, Erb K, Haberl H, Schulzb N. 2003. Ecological footprint time series of Austria, the Philippines, and South Korea for 1961–1999: comparing the conventional approach to an 'actual land area' approach. Land Use Policy, pp. 261–269.

Wackernagel M, Rees W. Notre empreinte écologique. Montréal : Ecosociété. 1999. 207 P.

Wernet F. 2004. Empreinte écologique d'une filière d'incinération des déchets industriels dangereux : rapport de stage de DEA. DEA Sciences et Technique du Déchets. Saint Etienne /Lyon : ENSMSE/ INSA de Lyon, 2004, 67p

Wiedmann T, Minx J, Barrett J, Wackernagel M. 2006. Allocating ecological footprints to final consumption categories with input-output analysis, Ecological economics 56, pp.28-46