

The ecological footprint of building construction

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Abstract

The aim of this paper is to evaluate the environmental pressure generated by the construction of two types of building, through the application of ecological footprint analysis. The appraisal of the impact of human settlement on the environment is of great concern and environmentally-friendly buildings are actually required. By considering the embodied energy of building materials and the “land area” required to sustain their assembly line, a comparison between the ecological footprint of two typical buildings in the context of Italy is presented. Finally, it is shown that the ecological footprint of building construction can be reduced by using environmentally-inexpensive materials, renewable energy resources and by optimizing bioproductive land use through the construction of multi-storeyed buildings.

Keywords: ecological footprint, embodied energy, sustainable urban planning, sustainable building construction.

1 Introduction

The current development of urban areas underlines the importance of focusing on cities, buildings and their importance for the human economy. It is also important to consider the consequences of urban area spreading on ecosystem health. Considering people’s tendency to live in urban areas, cities are becoming focal points for human life but unfortunately, they are not sustainable. They are cross-roads of most material and energy flows and, at the same time, they contribute to natural capital depletion.

Some concepts from evolutionary thermodynamics could be extended to the city in order to investigate its behaviour with a holistic approach. Each city can



be considered as an open system and depends on both interactions among its internal elements and exchanges with the external environment. Cities absorb high-quality fluxes of energy and matter from the outside as well as emitting wastes into the external environment (Tiezzi *et al* [1]). City dependence on external ecosystems shifts environmental impact from the local to the global level (Luck [2]). Houses, buildings, roads and infrastructure require a large amount of resources and can influence material and energy flows in urban areas. Cities can be considered as open evolutionary systems overflowing with structural and infrastructural fauna that feeds on natural capital.

This theoretical framework suggests analyzing cities in terms of entropy flows and entropy production or in terms of resource flows and waste production, leading to more sustainable urban planning.

Internal interactions and exchanges with the external environment are combined properties of evolutionary self-adaptive systems. These two categories also belong to urban dynamics that could be defined as dynamics of cities and dynamics *in* cities. For example, referring to dynamics of cities, flows of energy and matter that supply an urban system can be studied. Referring to dynamics *in* cities, patterns of urban interaction and their evolution can be studied.

This assertion leads to a new evolutionary approach for urban studies assuming that some properties and behaviour of an urban system will depend on both the interactions among its parts and between the system and its external environment.

This paper will focus on dynamics of cities, highlighting city dependence on external ecosystems, through the application of the ecological footprint analysis to buildings and their manufacturing process. The appraisal of the impact of human settlement on the environment is of great concern and more environmentally-friendly buildings are currently required. Considering the embodied energy of building materials, the energy spent in the construction process and therefore the “land area” required to sustain the building life cycle, the ecological footprint calculation of two typical Italian buildings is proposed. By optimizing the use of natural capital this analysis demonstrates how to reduce the ecological footprint of buildings, therefore leading to more sustainable building construction and city planning.

2 Resource consumption in building construction

The application of sustainable development principles to building construction aims to reduce resource consumption, waste production and environmental impact while warranting the high quality and utility of built-up areas.

In evaluating the dynamics of the construction industry it is important to consider the close interaction that exists between living and non-living structures. This interaction consists of material and energy flows, information and resource flows and it is necessary to understand the evolutive dynamics of the building as a system. In this contest house quality has to be assured while considering natural resources, social needs and national history. Any sustainable building should be able to:



- make the most of energy resources and natural capital;
- support a part of its energy demand through natural processes;
- use of renewable and local materials;
- reduce its influence on the water cycle;
- reduce CO₂ emissions and waste production;
- become part of the surrounding environmental, historical and cultural context.

About 40–50% of total energy cost in developed countries is closely linked or is a consequence of building construction. Moreover the construction of new buildings, infrastructure and industries, the production and the transport of building materials as well as waste disposal require an increasing amount of bioproductive areas. The significance of this impact requires its measure, here performed by ecological footprint analysis.

These and other global environmental and human-related issues encouraged an increasing number of designers, planners, developers and building users to provide more sustainable urban planning and building construction strategies. The application of sustainability principles and environmental accounting methods to building construction is a consequence of the global environmental problems and it aims to reduce the direct and indirect impact of construction industry with respect to two main issues:

- air pollution due to greenhouse gas emissions;
- depletion of both renewable and unrenewable natural resources (petroleum, natural gas, materials).

One of the main objectives of the application of environmental accounting methods to building construction is to evaluate the impact of common and alternative constructive technologies and materials. These types of analysis are characterized through a life-cycle approach and they are able to direct construction industry and materials choice towards a more sustainable building construction. Building ecology means using and managing natural resources considering not only their economic price and marketing availability, but also their real “environmental value”. Their availability in nature depends on time Nature spends for resource renewal and waste disposal and finally, on the Biosphere constraints.

3 Ecological Footprint Analysis

The Ecological Footprint Analysis (EFA) was proposed at the beginning of nineties by William Rees and Mathis Wackernagel.

Commonly the Ecological Footprint (EF) of a given population is defined as the ecologically productive land or sea area required to produce, in a sustainable way, all the resources and the ecological services population consume and to absorb, in a sustainable way, wastes and greenhouse gasses population produce, with the prevailing technology and resource management (Rees and



Wackernagel [3, 4], Wackernagel and Rees [5], Monfreda *et al.* [6]). Since people use resources from all over the world, and affect faraway places with their pollution, the footprint is the sum of these areas wherever they are on the planet.

EF is based on the assumption that most of energy and material flows can be converted into the bioproductive area that is required to maintain these flows. It is measured in global hectares (gha) and one global hectare is equivalent to one hectare of bioproductive land with world average productivity.

The account includes six types of bioproductive areas used to support human economy (Wackernagel *et al.* [7]):

- Cropland for the cultivation of food, animal feed, fibre, oil crops, and rubber;
- Grazing land for producing meat, hides, wool, and milk;
- Forests for harvesting timber, fuelwood, and wood fibre for paper;
- Fisheries for catching fish;
- Built-up areas, ecologically unproductive, used for accommodating infrastructure for housing, transportation, and industrial production;
- Energy land to sequester CO₂ emitted from energy and fossil fuels consumption.

EF has a *consumer approach* to sustainability issues that shows human appropriation and dependence on the natural capital.

Until now EFA was mainly applied to territorial system studies (at global, national or sub-national level) by comparing the EF of local population with the local regenerative capacity (Biocapacity). Biocapacity (BC) is defined as a measure of bioproductive supply, i.e. the biological production of a given area. It is an aggregate of the production of various ecosystems within the area, and it depends on both natural conditions and prevailing farming/forestry practices (Lewan and Simmons [8]).

EF has been recently applied to productive systems in order to evaluate natural capital appropriation, efficiency in natural resource use as well as pressure generating on the environment. Thanks to its consumer approach the application of EF to building sector can provide an interesting evaluation of building dependence on resource production and waste assimilation that occurs at the global scale. EF methodology can be applied to buildings depending on the following assumptions:

- it is possible to keep track of most materials used in a building;
- it is possible to calculate energy embodied in each material through specific *embodied energy coefficients*;
- use of fuels and energy during material construction and the building erection phase produces an increase of CO₂ emissions;
- embodied energy in building materials can be converted into the biologically productive area required to absorb CO₂ emissions or to produce materials.



However, compared to other “products” buildings are more difficult to evaluate for the following reasons. They are large in scale, complex in materials and function and temporally dynamic due to limited service life of building components and changing user requirements. Their production processes are much less standardized than most manufactured goods because of the unique character of each building (Scheuer *et al.* [9]).

It is simple to calculate the appropriation of bioproductive areas directly required for the physical occupation of land, with respect to dimension, typology and dwellers of a house. Unfortunately, the indirect appropriation of bioproductive land for CO₂ absorption and material production, represents one of the most important aspects of EF application to building construction. So EF is able to convert all inputs connected with the life cycle of a building in a single value, expressed in global hectare (*gha*). This value represents the direct and indirect appropriation of natural resources and ecological services of a building. According to Adalberth [10] total energy demand during the life cycle of a building is composed by the energy requirement for building construction (i.e. energy use for producing all the building materials and energy use during the erection phase), energy use during the renovation phase, energy requirement for transportation of materials, energy use during the operation and energy requirement for demolition. This study focuses on the embodied energy in building construction, neglecting energy requirements for transportation, operation phase and demolition.

This study aims to evaluate the consumption of natural resources and the efficiency of building constructional phases, trying to keep track of the most energy expensive factors or, in other words, the factors that more determine the appropriation of bioproductive areas. The appraisal of environmental impact of common and alternative construction methodologies and materials is necessary to reduce energy cost of buildings, emissions of CO₂ and EF of buildings. It has to be considered as a basic knowledge for a more sustainable building construction and urban planning.

3.1 Embodied energy and other coefficients

Embodied energy coefficients and the life-span of construction materials, expressed in MJ/kg and years respectively, are presented in Table 1. According to Scheuer *et al.* [9] it was decided to use 5% of total embodied energy in building materials to account for energy use during the erection phase (i.e. electricity used for power tools and lighting as well as diesel fuel used by heavy equipment at the construction site). Estimates for energy use during the erection phase range in literature from 1.2 to 10% (Cole *et al.* [11, 12]).

To convert the amount of primary materials, energy as well as built-up areas into the bioproductive “land area” required for building construction, the conversion factors proposed by Wackernagel *et al.* [13] are used. According to Wackernagel an emission factor of 0.020 kg of CO₂ for each MJ of average fossil fuel, a global CO₂ absorption factor of 0.095 kg/m² and an average production factor of 0.125 kg of timber for square meter of forest is used.



Assuming that energy expenses due to the use of natural products, such as timber and cork, are compensated by the absorption of CO₂ through trees during their growth, a hypothesis of zero emission factor has been considered.

Table 1: Embodied energy coefficients and life-span of building materials.

Type of material	Embodied energy (MJ/kg)	Life span of materials (years)
Gravel	0.2 _b	75 _b
Concrete	1.2 _a	75 _b
Structural steel	32.0 _a	75 _b
Asphalt	50.2 _b	75 _b
Hollow concrete bricks	0.7 _c	75 _b
Hollow clay bricks	2.5 _{a,b}	75 _b
Ceramic floor and wall tile	2.5 _a	75 _b
Ceramic tile - roofs claddings	2.5 _a	20 _b
Stoneware	18.93 _d	75 _b
Glass	15.9 _a	40-50 _d
Raw aluminium	191.0 _a	50 _d
Timber - veneer dried in autoclave	-	50 _b
Cement rendering	7.8 _a	5 _b
Cork sheets	-	40 _d

References in Table 1: *a* refers to data from González and Navarro [14]; *b* refers to data from Scheuer *et al.* [9]; *c* refers to our estimates on data coming from Venkatarama Reddy and Jagadish [15] and *d* refers to data from CRAS [16].

In order to evaluate the annual appropriation of natural resources and ecological services due to building construction, the life-span of each construction materials is considered. Adding up the annual contribution of every material the value of building ecological footprint is obtained.

4 Results and discussion

Here we discuss the results derived from the EF calculation of two typical Italian buildings with approximately 150 m² of housing surface for each floor:

- a. a two-storeyed detached house with a reinforced concrete structure, hollow clay brick walling, cork sheets insulation, aluminium window frame, timber door, ceramic wall and floor finishing and cement rendering claddings.
- b. a four-storey condominium built-up with the same materials and constructional process.



4.1 Building footprint

This section provides the results of EFA calculation underlining the dynamics involved in building construction and the appropriation of natural resources and ecological services through the selected buildings (Table 2).

Table 2: Comparison between the building energy and ecological values.

	Detached house	Four-storey condominium	Units
Built-up area	160	160	m ²
Total embodied energy	1,833	2,660	GJ
Housing surface	300	600	m ²
Embodied energy	6.11	4.44	GJ/m ²
Ecological Footprint	6,290	9,465	gm ²
EF/Built-up area	39	59	gm ² /m ²
Dwellers	5.2	10.4	inhabit.
EF per capita	0.122	0.091	gha per capita

Total embodied energy over the building life cycle ranges from 4.44 to 6.11 GJ/m² for the four-storey condominium and the detached house respectively. These values fall within the range of 2–12 GJ/m² cited in literature.

From an energy point of view, Table 2 shows that the embodied energy of the detached house is 30% smaller than that of the four-storey condominium. Moreover, from a landscape point of view the detached house is better integrated in the environmental, historical and cultural context of Italy. At the same time, thanks to its vertical growth the four-storey condominium is characterized by a wider housing surface that determines a minor embodied energy per square meter of housing surface.

EF values highlight that the construction of the selected buildings determines an annual bioproductive areas requirement of 6,290 and 9,465 gm² respectively. The direct requirement of real land for building construction, i.e. the built-up area, hides a consistent indirect requirement of bioproductive areas, needed to provide all raw materials and to absorb all CO₂ emitted in the constructional phase. For the detached house and the four-storey condominium this “ghost land” is 39 and 59 times as big as the built-up area respectively.

It is important to underline that the four-storey condominium is able to annually accommodate a greater number of dwellers by means of the wider housing surface. For the detached-house and the condominium, two and four apartments are in that order estimated. Considering that each apartment of the selected buildings is dwelled by a family as well as an average Italian family is made up of 2.6 people (ISTAT [17]), the detached house and the condominium annually accommodate 5.2 and 10.4 people correspondingly. This leads to an annual per capita ecological footprint value of 0.12 and 0.09 global hectares respectively.



These values are slightly greater than those proposed by Wackernagel pertaining to the typical Canadian wood-made houses. Results here obtained are more strictly related to reinforced concrete buildings that are typical of the European building construction. All these characteristics make the results obtained applicable to the analysis of the ecological footprint of Italian territorial systems.

Moreover it is interesting to compare these results with the worldwide average biocapacity per capita (1.90 gha), defined as the annual amount of bioproductive land that people should have at their disposal by means of the equal distribution of natural resources. The percentage of EF that each average Italian citizen requires for building construction ranges from 4.8% (four-storey condominium) to 6.4% (detached house) of the overall biocapacity. Finally it is possible to compare EF values with the Italian average biocapacity, 1.18 gha per capita. EF component due to building changes to 7.7% and 10.4% respectively.

Thus, through the construction of multi-storeyed buildings it is possible to reduce both the direct and indirect demand of built-up and bioproductive areas correspondingly. For allocating 10 dwellers the selected four-storey condominium requires about 160 m² of built-up area; at the same time, for allocating the same number of dwellers, two detached house are requested. This leads to an increase of built-up areas that replace natural bioproductive areas contributing to the depletion of the global natural capital. This is even more important considering the continuous increase of the world population and the global tendency to live in urban areas.

Keeping in mind Earth biophysical constraints, biogeochemical cycle dynamics and natural rate of resource production in regard to human rate of consumption, is necessary to direct future building planning towards more environmentally-inexpensive buildings.

4.2 Unpacking the ecological footprint of building construction

To deeper understand the EF values of the selected buildings, data are presented for both building structural elements (see Table 3) and building materials (see Table 4).

Focusing on “land area” categories, Table 3 shows that the construction of a typical Italian building requires a large amount of *Energy land* (90%) while requiring *Forests* and *Built-up areas* in a small scale (about 5% each of them).

Focusing on structural elements, high demand of natural capital for *Foundations* is evident. This category includes consolidation and foundation works. It is interesting to compare the bioproductive land requirement for *Foundations* by the detached house and the four-storey condominium. It ranges from 33% to 23% of the total footprint value respectively. These values underline the environmental cost of *Foundations* in building construction. Most of natural resources and ecological services are required for this structural element which more contributing to the global natural capital depletion. Thus, in the construction of a building it is very important to optimize environmental costs by means of multi-storeyed buildings.



Table 3: Ecological footprint by structural elements and types of land areas of the selected buildings.

Detached House	Energy land gm ²	Forest gm ²	Built-up area gm ²	TOTAL gm ²	%
Foundations	2,058	-	-	2,058	33%
Structure and slabs - ground floor	1,139	-	-	1,139	18%
Structure and slabs - 1st floor	1,059	-	-	1,059	17%
Roof structure and claddings	842	-	-	842	13%
Floor and wall tiling and plastering	190	-	-	190	3%
Window and door frame	325	194	-	519	8%
Sanitary fittings	20	-	-	20	0.3%
Insulation	-	116	-	116	2%
Built-up area	-	-	347	347	6%
Total ecological Footprint	5,633	310	347	6,290	100%
Four-storey condominium	Energy land gm ²	Forest gm ²	Built-up area gm ²	TOTAL gm ²	%
Foundations	2,165	-	-	2,165	23%
Structure and slabs - ground floor	1,139	-	-	1,139	12%
Structure and slabs - 1st floor	1,059	-	-	1,059	11%
Structure and slabs - 2nd floor	1,059	-	-	1,059	11%
Structure and slabs - 3rd floor	1,059	-	-	1,059	11%
Roof structure and claddings	842	-	-	842	9%
Floor and wall tiling and plastering	452	-	-	452	5%
Window and door frame	682	388	-	1,070	11%
Sanitary fittings	41	-	-	41	0.4%
Insulation	-	231	-	231	2%
Built-up area	-	-	347	347	4%
Total ecological Footprint	8,499	619	347	9,465	100%

Table 4 shows natural capital appropriation through building materials. For the detached house, most of EF value is due to the use of *Concrete* (for *Foundations* and *Structure and slabs*) and *Asphalt* (for foundation waterproofing). *Asphalt* is an environmentally-expensive material with a high embodied energy per mass unit. It requires a large amount of *Energy land* for its production even if it is used in a very small quantity. EF component due to *Asphalt* ranges from 21% for the detached house to 14% for the four-storey condominium. Once more EF values demonstrate the need of a more sustainable building construction by choosing multi-storeyed buildings able to reduce the Ecological Footprint of building construction system. Moreover, the choice of multi-storeyed buildings causes an important reduction in soil waterproofing, and decreases the risk of the water cycle alteration.

In addition to this, it is important to underline the contribution of aluminium to total bioproductive land requirement. *Raw aluminium* has an extremely high embodied energy per kg and it is used for door and windows frame. The EF value of a raw aluminium window frame (size: 1.3 m x 1.5 m x 0.04 m) is about 30 gm² of *Energy land* while a timber window frame with the same size requires about 2 gm² of *Forests*. These results demonstrate the importance of natural products in building construction. The choice of energetically-inexpensive and environmentally-friendly materials like timber can reduce the ecological footprint of *Window and door frame* up to 90%.



Even if this category contributes only in a minor part to the overall building footprint, it is possible to reduce total natural capital appropriation of buildings up to 3.5% by choosing these materials. Note that these types of precautions could be extended to all building structural elements.

Table 4: Ecological footprint by building materials and types of land areas of the selected buildings.

Detached House	Energy land gm ²	Forest gm ²	Built-up area gm ²	TOTAL gm ²	%
Gravel	96			96	2%
Concrete	1,656			1,656	26%
Raw steel - reinforcement	947			947	15%
Asphalt	1,349			1,349	21%
Hollow concrete bricks	742			742	12%
Hollow clay bricks	90			90	1%
Ceramic	183			183	3%
Ceramic tile - roofs claddings	223			223	4%
Stoneware (grès)	16			16	0.3%
Glass	38			38	1%
Raw aluminium	287			287	5%
Timber - veneer dried in autoclave		194		194	3%
Plaster	7			7	0.1%
Cork sheets		116		116	2%
Land use			347	347	5.5%
Total ecological Footprint	5,633	310	347	6,290	100%

Four-storey condominium	Energy land gm ²	Forest gm ²	Built-up area gm ²	TOTAL gm ²	%
Gravel	111			111	1%
Concrete	2,619			2,619	28%
Raw steel - reinforcement	1,501			1,501	16%
Asphalt	1,349			1,349	14%
Hollow concrete bricks	1,376			1,376	15%
Hollow clay bricks	154			154	2%
Ceramic	438			438	5%
Ceramic tile - roofs claddings	223			223	2%
Stoneware (grès)	32			32	0.3%
Glass	68			68	1%
Raw aluminium	614			614	6%
Timber - veneer dried in autoclave		388		388	4%
Plaster	14			14	0.1%
Cork sheets		231		231	2%
Land use			347	347	3.7%
Total ecological Footprint	8,499	619	347	9,465	100%

Finally, it should be taken into account the fact that timber, cork and other wood products are able to compensate the CO₂ emissions that rise from their use through the negentropic work of the photosynthesis.

5 Conclusions

By integrating a common embodied energy analysis with EFA it is possible to assess not only energy expenses but also natural capital appropriation of buildings, adding up all inputs into a single value. Based on these parameters the



assessment of building impact, enables to find a common language between architectural and ecological disciplines and to generate useful analysis for establishing sustainability parameters for building construction and urban planning.

Results presented in this paper demonstrate the minor environmental pressure generated by multi-storeyed buildings, in respect to detached houses, in the Italian contest. Minor natural capital requirement in multi-storeyed buildings is due to:

- major number of dwellers for each building;
- sharing of *Built-up area*;
- less requirement of bioproductive land and more natural capital saving;
- Optimization of the environmental burdens due to environmental expensive structural elements (i.e. *Foundations*).

In addition to this, it is important to consider the land area saving that results through the use of local building materials and renewable energy sources in the building constructional phase.

EFA by building materials shows the importance of natural materials like wood and cork in CO₂ reduction and, in general, in the reduction of “ghost land” requirement.

Finally, it is undeniable the importance of saving the natural capital, the actual limiting factor. So, thanks to the application of EFA to building construction it is possible to assess building appropriation of the natural capital and to suggest useful options reducing this appropriation.

For this reasons, this article suggests a comparison between the EF values of the two typical Italian buildings and both the global and the Italian average per capita BC. The appropriation of natural resources and ecological services for building construction ranges from 4.8% (four-storey condominium) to 6.4% (detached house) of the overall BC, while it changes to 7.7% and 10.4% respectively if compared with the local average BC.

House sharing, the reduction of *Built-up area* as well as choosing natural materials and multi-storeyed buildings is necessary to reduce and optimize the appropriation of bioproductive land in building construction. All these precautions foster the conservation of the natural capital and the reduction of CO₂ emissions for the benefit of current and future generations.

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