CHAPTER 1

INTRODUCTION

1.1 *Background*

An ecological ethics has arisen during the last few decades. Environmental global changes, growing pollution and natural resources depletion created new ecological concerns that shifted our perception of the world. Environmental issues have no boundaries, leading to a global consciousness that every human action has effects at different geographical, temporal and biogeochemical systems scales. From a man-centered vision of life (anthropomorphic), humankind started to move gradually to a network vision of phenomena (systemic).

These social and technological environmentalist movements promoted the questioning of the intrinsic role of the human world within the larger planetary scale. These discussions around the coupling of the human world with the natural world emphasized the problems of waste disposal, resources depletion and environmental degradation.

This new awareness for the environmental impacts of manufacturing processes, waste management and pollution control introduced a new terminology based on analogies with nature and ecosystems. This biotic transformation of technical language includes metaphors such as 'ecology', 'metabolism', 'life-cycle', 'green', 'symbiosis', 'ecosystem', or 'food', that become a common vocabulary crossing all industrial and research activities, first, and later expanding into the discourse of politicians, decision-makers, NGO's, and people in general.

In this context, Ayres (1989) presented the idea of 'industrial metabolism' to describe the resemblances between industrial systems and biological systems. The analogy showed the biosphere and the technosphere both as materials-processing systems driven by a flow of free energy, and as self-organizing dissipative systems in a stable state, far from thermodynamics equilibrium. While survival is the element that regulates natural systems, industrial production not being self-regulated is regulated by the human factor. This happens because industrial activities integrate a demand-supply chain, being the broader economic system the truly regulatory mechanism of the industrial metabolic activities (Ayres, 1994).

In the metabolic analogy, the production system is a primitive living organism in an early evolutionary stage, being a process that transforms raw materials into products and waste by using energy and human labor. Ultimately, this metaphoric concept enlightened the need for industry to learn from the biosphere how to change the common production system into a regenerative and efficient process. Industrial metabolism represents the whole of energy and materials flows going through the industrial system. The concept is based on an analytical and descriptive approach using the materials balance principle in order to understand the circulation of energy and materials flows linked to human activities on a life cycle perspective, i.e. from extraction to the reintegration into the overall biogeochemical cycles (Erkman, 1997).

The holistic idea of an industrial metabolism developed later into a higher level by addressing the concept of 'ecology' to industry. While the metabolic analogy represents the industrial process that leads to a manufactured product as a biological organism, a more effective ecological analogy such as 'industrial ecology' represents the network of industrial processes as an ecosystem (Frosch, 1992; Erkman, 1997). The idea of an 'industrial ecosystem' pointed to the recognition that the traditional manufacturing processes should be transformed into a more integrated Model functioning as an analogue of biological ecosystems (Frosch & Gallopoulos, 1989).

Such a system would optimize consumption of energy and materials, while minimizing waste generation, the effluents of one process would serve as raw material for the other process. This parallel between the organic and the industrial is more explicit in Graedel (1996), who compares Biological Ecology and Industrial Ecology by identifying a set of common characteristics and system behaviors (see Table 2.1).

Table 1.1. Analogy between Biological Ecology and Industrial Ecology proposed by Graedel (1996).

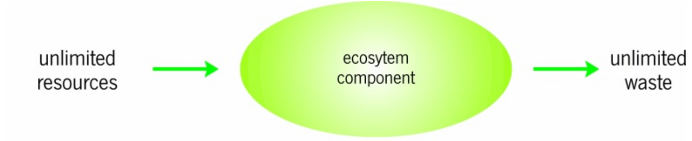
Characteristic	Biological Ecology	Industrial Ecology
Independent activity	All can take actions on their own behalf	Factories undertake essentially independent activities: acquisition of resources, transformation of resources
Resources consumption	Expend energy to transform materials into new forms suitable for use	Expend energy transforming materials into new forms suitable for use
Waste release	Excess energy and materials residues are released into the surroundings	Energy and materials residues (heat, solid waste, liquid waste, gaseous emissions) are emitted into surroundings
Capacity of reproduction	Able to reproduce their own kind	Not re-creation itself, but creation of nonorganismic products
Response to external stimuli	Relate to factors as temperature, humidity, resource availability, and so on	Relate to external factors as resource availability, customers, prices
Stages of growth	Originate as one cell and move through stages of growth	Do not follow the predictable progression of life stages
Finite lifetime	Have variable, but finite, lifetimes	Have a finite lifetime

The concept of Industrial Ecology comprises a systemic view of the interaction between industrial and ecological systems (Garner & Keolsian, 1995) addressing the environmental effects on both the abiotic and biotic components of the ecosphere. In spite of all definitions for 'industrial ecology', Erkman (1997) establishes three key concepts for a common perspective:

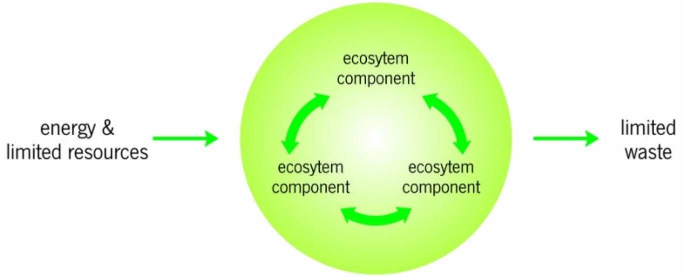
(i) It is a systemic view of the entire industrial economy and its relationships with the biosphere;
(ii) It emphasizes the biophysical context of all human activities;
(iii) It considers technological dynamics as a crucial factor for the transition to a viable industrial ecosystem.

An important aspect of the systemic approach to industrial processes, including the construction industry, is the turning point from a closed linear production system (metabolic) into an open interactive and cyclic production system (ecologic). In order to build a biological analogy for industrial productive systems, three types of evolutionary ecosystems have been pointed out (Jelinsky *et al.*; 1992; Graedel, 1996, Lifset & Graedel, 2002) (see Figure 1.1):

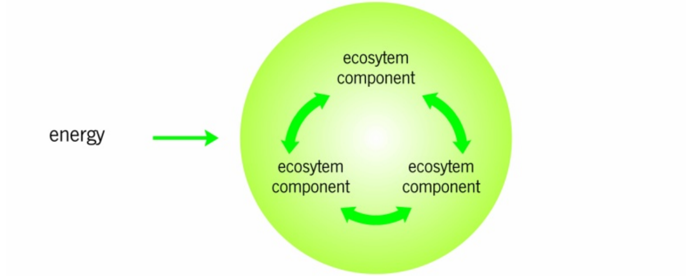
(i) Type I systems are linear and characterized by a flow of a material from one stage to the next that is independent of all other flows in a scenario of 'unlimited' resources;
(ii) Type II systems are quasi-cyclic and characterized by quite small flows of resources into the system and small flows of waste outputs, creating large flows of materials inside the system due to resources scarcity;
(iii) Type III systems are cyclic and the waste of a component of the system becomes a resource to another component at different temporal and spatial scales.



(a) Type I: flows of materials in a linear system



(b) Type II: flows of materials in a quasi-cyclic system



(c) Type III: flows of materials in a cyclic system

Figure 1.1. Types of evolutionary ecosystems, adapted from Jelinsky *et al,* (1992), Graedel (1996) and Lifset & Graedel (2002).

The advent of Industrial Ecology brought a new vision regarding environmental responsibility of manufacturers and users of materials and products. Shaped in turn of the analogy with ecological ecosystems, the field of industrial ecology found in the biotic metaphors a new way to understand and explain the behaviors of manufacturing processes and their relationship with nature, underlining the vision of a global earthen system.

Thus, as a consequence of this new understanding about environmental impacts and concerns with resources depletion, which have been progressively translated into regulations and presented in market demands, industrial processes started to move from a Type I system to a Type II system, and ultimately and ideally to a Type III system.

This shift in industrial processes enhanced materials recovery and materials flow reduction, as part of the main goals to achieve a sustainable production system. The carrying capacity of natural systems pointed out the limits of the natural capital and the limits of an economic growth based upon the input of virgin materials in the production systems, i.e. manufactured capital.

In modern societies, human wealth ‘depends’ on the use and consumption of natural resources, such as materials, energy and land. Therefore, Sustainable Resources Management became the key concept for ensuring that the material basis of society and economy expressed by resource demands and waste disposal, i.e. total material requirements, would not exceed the carrying capacities and tolerable limits of nature and society (Bringezu, 2002; EEA, 2005):

(i) Extraction of resources and emissions to the environment can only be continued if those flows do not exceed the finite spatial-temporal capacities of the environment to act as a feedstock and as a sink;

(ii) The physical growth of the technosphere must assure the equilibrium between resource extraction and residual release.

In this context, several international organizations and governments, such as the European Union, adopted approaches as the ‘Factor 4 to 10’. The ‘Factor 4 to 10’ concept enhances the importance of natural resources conservation, proposing a utility and economic value added to products with reduced resource requirements. Applying the ‘Factor 4 to 10’ to economies means reducing global resource extraction by half, and increasing the efficiency of primary resources demand by 4 to 10 times in the next 30 to 50 years (Gardner & Sampat, 1998; Bringezu & Schutz, 2001, Bringezu, 2002; Kibert, 2005).

However, materials consumption tends to increase. A first estimate of the total material consumption in the industrialized countries ranges between 31 and 74 tonnes per capita, which could amount to a worldwide consumption between 279 and 666 billion tonnes for a growing world population of 9 billion in the next 50 years with the same societal needs fulfilled (EEA, 2005).

Sustainable management of material flows occurs at different environmental scales and aims to:

(i) Reduce resources depletion;

(ii) Reduce environmental impacts of materials extraction and use, such as ecotoxic effects, physico-chemical changes, loss of biodiversity, nutritional effects, and landscape changes;

(iii) Reduce waste disposal.

Therefore, saving natural capital and reducing pressure on natural carrying capacities may be achieved by implementing a waste minimization strategy (see Figure 1.2). Waste minimization definition is a broader concept than waste prevention, because it also includes waste management measures such as quality improvements and recycling (Jacobsen & Kristofferson, 2002).

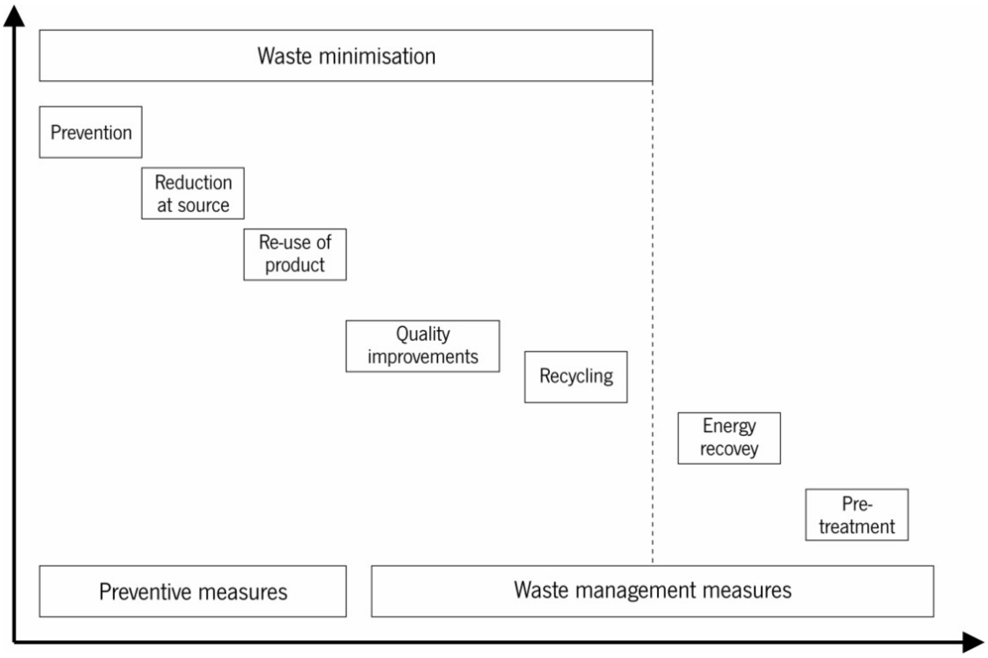


Figure 1.2. OECD working definition on waste minimization (Jacobsen & Kristofferson, 2002).

In this framework, waste minimization practices would include the following actions:

- (i) Dematerializing, i.e. to decrease raw materials inflows into and accumulation in the economy (Bartelmus, 2002);
- (ii) Improving the efficiency of resources use, i.e. to prevent the wastage and degradation of these resources (Fatta & Moll, 2003);
- (iii) Reducing landfill and increasing materials recovery, i.e. closing materials loop by maximizing reuse and recycling industrial processes.

In spite of increases in recycling widely observed in most countries of the European Union, landfilling is still the main waste treatment solution (EEA, 2007). The increase on recycling is due to policy instruments such as the Packaging Directive (EU, 1994) and the Landfill Directive (EU, 1999), or to earlier national regulations.

In a waste minimization context, output flows from systems become a new source of resources as long recycling processes and technologies evolve to turn these processes economically and environmentally feasible. Furthermore, the recovery of materials becomes an essential action in order to abide by market demands and environmental policies, such as the implementation of the Extended Producer Responsibility to small electronic products and automotive products.

Extended Producer Responsibility (EPR) raised a new perspective on the management of end of life products with a view to closing materials loop, and developed new approaches to products design and manufacturing processes. However, construction industry is far away from that goal, due to a set of specific characteristics, notably the following:

(i) Long lifespan of building products when compared with other type of current products;
(ii) Number of intervenient in the construction process, such as contractors and sub-contractors for specific tasks and deliveries;
(iii) Adaptive reuse of buildings.

In the construction industry, building deconstruction appeared as an approach to waste minimization and closing materials loop, being an alternative for traditional demolition activities that produced great amounts of mixed waste which are in great part currently landfilled.

In the United States of America, construction and demolition waste (C&DW) generation is estimated to be 136 million tonnes per year, which was equal to 1.27 kilograms per capita per day (EPA, 1998). Chini & Bruening (2005) presented an increase of C&DW generation up to 157 million tonnes, of which only 39 million tonnes are recovered.

In Japan, the amount of C&DW generated was approximately 99 million tonnes in 1996, decreasing to approximately 85 million tonnes in 2001, while the recycle ratio increased from 57% in 1996 to 81% (Nakajima, 2005).

In the European Union, C&DW was estimated to be 180 million tonnes per year (see Table 1.2) of which just 28% was recycled or reused (Symonds, 1999). These numbers tend to increase as observed actually in some countries. In Germany, C&DW generation increased to 72 million tonnes average per year, but also recycling of C&DW increased and only 10% average are currently disposed of (Sunke & Schultmann, 2008). In the Netherlands, C&DW generation increased to 19 million tonnes in 2000 and to 24.96 million tonnes in 2003 (Durmisevic, 2008).

Table 1.2. C&DW arising and recycling (Symonds, 1999).

Member State	'Core' C&DW arisings (M tonnes, rounded)	% Re-Used or Recycled	% Incinerated or Land-filled
Germany	59	17	83
UK	30	45	55
France	24	15	85
Italy	20	9	91
Spain	13	<5	>95
Netherlands	11	90	10
Belgium	7	87	13
Austria	5	41	59
Portugal	3	<5	>95
Denmark	3	81	19
Greece	2	<5	>95
Sweden	2	21	79
Finland	1	45	55
Ireland	1	<5	>95
Luxembourg	0	n/a	n/a
EU-15	180	28	72

Building deconstruction can be defined as a selective demolition, where materials are taken off the building in a way that allows their subsequent separation and reuse. Main constraints to building deconstruction are related with disassembly capability (Kibert, 2003). Current deconstruction of buildings faces the problem of establishing overall dismantling sequences, mainly because the buildings that are being dismantled today were not conceived for deconstruction.

These constraints lead to new building design frameworks, such as Design for Disassembly/Deconstruction (DfD). These approaches were not completely new as they were already in practice in assembly/disassembly lines in the manufacturing industry, such as electronics and automotive (Lambert, 2002, 2003; Lambert & Gupta, 2005). However, unique characteristics of buildings as products, such as their size, complexity or long lifespan, raised specific problems within the context of building waste minimization and materials recovery.

DfD may be defined as conceiving a product in a way that its materials and components may be more easily recovered after their Service Life, so that they can be reused or recycled.

Principles for DfD of buildings were proposed in order to deal at the design stage with the key aspects that could enable disassembly (Poon & Jaillon, 2001; Thormark, 2001; Crowther, 2003), such as material properties, type of connections, standardization, flexibility and information.

Life cycle coordination was also recognized as a key aspect of building waste minimization in DfD (Crowther, 2001; Durmisevic & Iersel, 2003) by ensuring that building design is optimized for the required Service Life of materials and components.

Approaches to assess different aspects of DfD in building construction were also proposed. Thormark (1998, 2000, 2001, 2002, 2006) proposed the recycling potential approach in order to express how much of all embodied energy and natural resources used in a building or a building element, it is possible to recover after demolition by means of recycling processes. Durmisevic *et al.* (2003) proposed the disassembly potential approach as a measure of the ability of a building's structure to be dismantled for the reuse and recycling of materials and components.

DfD in building construction is actually one of the key aspects of the Construction Ecology approach, because it enhances the importance of building waste minimization management, by integrating Service Life Planning, technological solutions for easy disassembly, and the assessment of the building materials and components recovery in order to close the loop in the most effective way.

1.2 *Statement of the problem*

From the systems analysis point of view, the first two laws of Thermodynamics state the principle of conservation of energy and matter (First Law), and that entropy in closed systems is likely to increase (Second Law).

Materials processing converts low entropy materials, such as mineral ores or fossil fuels, in high entropy materials, i.e. waste, by using available energy. On the contrary, materials recycling processes requires energy to convert those high entropy materials back again into low entropy materials.

However, due to the Second Law, recovery processes will not be very efficient. The closed cyclic system processes, i.e. a Type III system (see Figure 1.1), are only possible assuming that wastes produced in secondary recovery will be recycled by other system that will actively act over a global 'wastebasket' (Ayres, 1999). Ultimately, the Earth itself will be such recycling system. As an example, carbon is recycled elsewhere outside of the system that produced it by the plants through photosynthesis process using low entropy solar energy.

According to these principles, environmental concerns with resources management moved industrial manufacturing processes from an open system to a quasi-cyclic system, where dissipative losses of matter and energy occur during the use and transformation of materials and energy.

As systems tend to thermodynamic equilibrium, there is a loss of quality in materials and energy, which manifests by decay in the physical properties of materials, i.e. degradation, or in dissipation of energy in the form of heat. Thus, in materials reuse or recycling processes of materials is needed to regain 'quality' in order to achieve material or product requirements, by adding energy and new materials during the processes.

Within this approach, the contribution of building deconstruction and materials recovery for minimizing environmental impacts of material flows should not be evaluated from a quantitative point of view, i.e. in terms of how much is the amount of recovered materials, or by assessing disassembly capability. Instead, thermodynamic principles emphasize quality aspects of recovered materials as constraints for closing the loop in a waste minimization framework, what could be defined as 'Effectiveness'.

Properties influencing quality aspects of materials and components are the following:

(i) Loss of shape;
(ii) Degradation;
(iii) Purity.

Thus, environmental contribution of materials recovery should be assessed mainly by evaluating recovered materials qualities that influence feasibility of End-of-Life Scenarios, taking in account the natural resources that are being saved, i.e. natural capital, and preventing high entropy materials to be dissipated in the Earth global system. In general, high entropy materials have high performance capabilities (Brown & Buranakarn, 2003), i.e. durability, mechanical resistance, such as steel, concrete, or plastics.

1.3 *Scope of the study*

The study of environmental issues in turn of materials, or in particular building materials, can be extensive, but the aim of this study is limited to materials recovery aspects from a waste minimization perspective.

Approaches to assist products design and development that appeared during the last two decades, such as Life Cycle Management, Life Cycle Appraisal, Design for Environment, and Design for Life Cycle, or environmental assessment methodologies such as Life Cycle Assessment and Material Flows Analysis, are not covered by this study.

Thus, the scope of this study will be on discussion of the concept of Effectiveness, notably on how effectiveness of materials recovery can be assessed through systems analysis.

The main emphasis will be on identifying the main constraints on the quality of recovered materials and ultimately the feasibility of End-of-Life Scenarios, as well as, on how those constraints can be translated into an assessment Model.

1.4 *Objective of the study*

The objective of this study is to propose the principles for a methodology to evaluate the effectiveness of building materials and components recovery. The formulation of such principles will be the core of the proposal for an assessment Model to be applied on the evaluation of a building during the design stage.

For the development of these principles, the following issues will be considered:

(i) Factors influencing materials recovery through deconstruction and disassembly operations such as type of connections;
(ii) Factors influencing the quality of recovered materials and ultimately the feasible End-of-Life Scenarios such as Service Life;
(iii) Feasible waste management solutions, with emphasis in Reuse and Recycling scenarios.

The proposed Model will express the degree of materials recovery effectiveness, by estimating a qualitative index. This index will be estimated as a qualitative reference taken into account the overall design solution regarding the amount, the quality, and the most feasible waste management solutions for the recoverable materials and components.

The proposed Model will be applied mainly at two levels:

(i) Building element (e.g. wall, roof, structure, façade);
(ii) Whole building.

Furthermore, the proposed Model will have different applications such as for a single assessment, for comparative assessment of different solutions, and for the improvement of the overall or part of the design solution.

1.5 *Introduction to the thesis*

The thesis is a discussion on the concept of materials recovery effectiveness and on how effectiveness can be assessed through the proposed Model.

An overview of the thesis framework includes:

(i) A general presentation of building deconstruction and Design for Deconstruction/Disassembly principles;
(ii) A discussion of systems analysis methodologies;
(iii) The proposal of a Model to evaluate the effectiveness of materials recovery;
(iv) The development of necessary data for the proposed Model's database;
(v) The assessment of the proposed Model.

Chapter 1 is an introduction to the background of materials recovery practices, with relevance for Industrial Ecology and environmental policies, in which principles it is grounded.

Chapter 2 is a discussion on the main factors influencing the amount and quality of recovered materials in building deconstruction operations and DfD principles. A parallel with other industrial practices is established, with emphasis on how those industries are dealing with waste minimization and materials recovery.

In Chapter 3, aspects related to DfD are discussed namely Service Life, recovery alternatives, and recovery rates for materials and components. In this chapter, the current approaches to Service Life estimation of building materials are discussed. Definitions of Service Life and estimation methods are identified, and a survey on available data on Forecast Service Life is performed. Also feasible recovery alternatives for a set of different types of building materials are presented, and each group of materials is analyzed in detail regarding the current research on reuse, recycling and energy recovery scenarios, with an emphasis on the most common materials and applications. Finally, in Chapter 3, data on recovery rates of building materials in deconstruction operations are discussed.

Chapter 4 is a general approach to eco-thermodynamic principles of materials life cycle and recovery processes. Emergy accounting is here proposed as the assessment methodology to effectiveness assessment. Other methods, such as Embodied Energy Analysis and Exergy Analysis are compared. The application background of Emergy accounting to building construction and materials is also discussed.

Chapter 5 is the proposal of a framework for a Model to evaluate materials recovery effectiveness using Emergy analysis by establishing a Deconstruction Effectiveness index (DE). The theoretical approach behind the development of the proposed Model, its framework and calculation procedures are discussed in this chapter.

In Chapter 6, the calculations of Specific Emergy for a set of building materials are performed. A survey on other available specific Emergy values is also performed. This information will be also part of the proposed Model's database.

In Chapter 7, the proposed model is applied at two different levels: building element and whole building. First, an application to three types of internal walls (brick masonry, plasterboard, and wood frame) allows a more detailed evaluation of the proposed Model, by easily managing the different variables that might influence the Deconstruction Effectiveness index (DE). Changes on Forecast Service Life, End-of-Life Scenarios and Recovery Rates are made to evaluate if the proposed Model acts according to the theoretical principles. The application level of the proposed Model to three types of construction systems (concrete, wood, and steel) allows the evaluation of the Model behavior when applied to more complex systems.

Chapter 8 comprises a discussion on the Model, namely aspects that might be improved in the future, possible integration with design tools, and general orientations for further research.

CHAPTER 2

BUILDING DISASSEMBLY/DECONSTRUCTION

2.1 *The environmental approach of building construction*

The concept, future directions and promises of Industrial Ecology theory have been widely discussed and the potential for greening the industrial systems has been highlighted. The metabolic activities of the earlier industrial processes that were supported by linear models of production, i.e. natural resources consumption, manufacturing, and wastage, has moved gradually to quasi-cycle models (Jelinsky *et al.* 1992, Graedel, 1996, Lifset & Graedel, 2002) where reuse and recycling paths replaced partially the wastage of materials and products. This shift changed the production paradigm and industrial manufacturers are progressively including new environmental concerns in manufacturing and recovery of materials and products. These concerns embrace both energy efficiency and materials consumption.

Energy efficiency concerns were easily assimilated by industrial manufacturers because energy has a high cost. Also public and environmentalists concerns regarding the greenhouse effect shifted the traditional market demands into an energy efficient one, both for production lines and products performance.

In addition, direct pollutant effects of industrial production were easily pointed out, as emissions from factories in the form of contaminated sewage and gases degraded the surrounding environment, polluting water streams and creating smog.

On the other hand, the real costs of resources consumption were not so clearly for manufacturers as raw materials concentrated elsewhere were entering the production line and getting out as manufactured commodities for using and discarding elsewhere. However, resources depletion, and the fact that the carrying capacity of natural systems was not able to absorb the amount of waste generated during the life cycle of a product, put the focus also on materials.

Environmental impacts of mining, harvesting and landfilling activities were pointed by several researchers, regarding the direct effects of such activities for air pollution, loss of biodiversity, and soil and water contamination.

New public awareness forced politicians to adopt new environmental legislation concerning waste minimization, such as the Packaging Directive (EU, 1994), the Landfill Directive (EU, 1999), the implementation of the Extended Producer Responsibility concept, such as the End of Life Vehicles Directive (EU, 2000) and the Directive on Waste Electrical and Electronic Equipment (EU, 2003). The increase of landfill taxes also promoted a new awareness among industrial manufacturers regarding waste discarding, which started to change the traditional structure of industrial manufacturing processes.

Vertically integrated remanufacturing processes or involving cooperative agreements showed successful results regarding resources savings (Clegg & Williams, 1994; Ayres *et al.*, 1997): remanufacturing at Rank Xerox saved about 55 million dollars in 1993, and the raw materials savings increased to almost 70 million dollars in 1995, reduced landfill requirements by 7000 tons per year, and mineral resources consumption.

Despite the global increase of municipal solid waste generation in EU-25, by implementing the Landfill Directive (EU, 1999) in the European Union, the global amount of municipal solid waste landfilled is actually decreasing (see Figure 2.1) due to product's recovery policies.

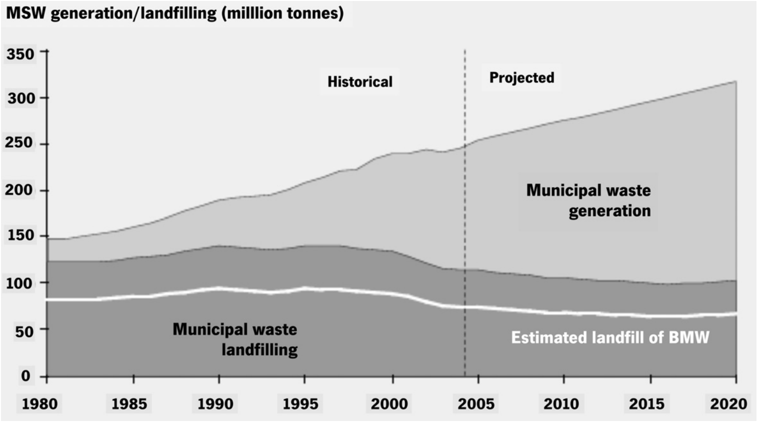


Figure 2.1. Projected generation and landfilling of municipal waste in the EU-25 (EEA, 2007).

The traditional market of products became the new 'green' market, being the 'green' labelling the metaphor for a nature friendly product, normally recyclable and produced from sustainable resources.

As building activities and buildings are commonly known as being responsible for a great amount of natural resource consumption all around the planet and highly energy intensive especially during buildings usage, the recognition of the environmental impacts of such activities turned to a biological metaphor of building construction and building materials to understand and explain the problem.

Roodman & Lenssen (1995) describe several impacts of modern buildings on people and on environment, stressing the use of virgin materials, water, and energy resources, and waste generation (see Table 2.1).

Table 2.1. Impacts of modern buildings on people and the environment, adapted from Roodman & Lenssen (1995).

Problem	Building's share problem	Effects
Use of virgin materials	40% of raw stone, gravel, and sand, comparable share of other processed materials such as steel	Landscape destruction, toxic runoff from mines and tailings, deforestation, air and water pollution
Use of virgin wood	25% for construction	Deforestation, flooding, siltation, biological and cultural diversity losses
Use of energy resources	40% of total energy use	Local air pollution, acid rain, damming of rivers, nuclear waste, risk of global warming
Use of water	16% of total water withdrawals	Water pollution, competes with agriculture and ecosystems for water
Production of waste	Comparable in industrial countries to municipal solid waste generation	Landfill problems, such as leaching of heavy metals and water pollution

Approaches and concepts such as ecology of building materials (Berge, 1992), building cycle (Hendriks *et al.*, 2000), construction ecology (Kibert, 2002; Kibert *et al.*, 2002), and building ecology (Graham, 2003) were proposed.

Rather than global concepts as sustainable construction or sustainable buildings, the former are especially committed to the understanding of the metabolic activities of the construction industry in order to improve materials consumption efficiency and to minimize construction waste.

According to Kibert (2002), the aim of construction ecology is to:

> *...provide a theoretical basis for understanding the optimal design of the built environment and relies heavily on several branches of ecology, such as systems ecology, adaptive management, and exergy analysis.*

Berge (1992) proposed a global view (see Figure 2.2) in order to enhance aspects of resource consumption and pollution effects during production processes of materials and components, and also during the building construction process and building usage phases.

The cycle analogy is also put forward by Hendriks *et al.* (2000) to propose a waste minimization in building construction, by describing the available technologies and procedures for materials recovery, with emphasis on reuse and recycling paths for building materials waste.

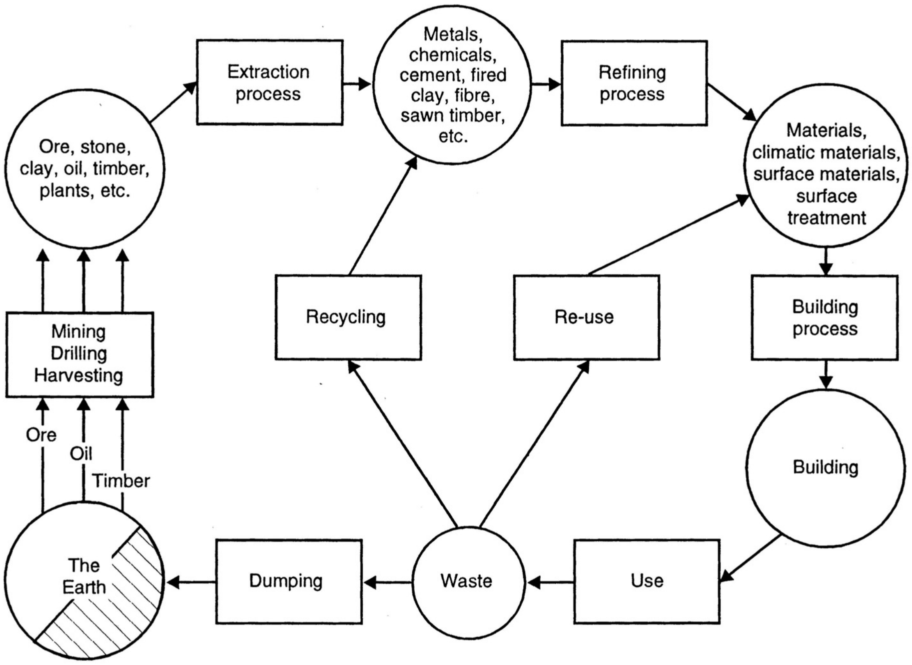


Figure 2.2. The cycle of materials, from Berge (1992).

Kibert (2002) and Kibert *et al.* (2002) put the emphasis on how building industry metabolism may act according to biological systems in the sense of closed-loop materials for buildings as a central question, side by side with energy efficiency in order to achieve sustainability goals. Such an ecological approach would transform the built environment so as to give it the following characteristics:

(i) Readily deconstructable at the end of life cycle;
(ii) Easily repaired by means of demountable components;
(iii) Composed by products designed for recycling;
(iv) Recyclability of bulk structure materials;
(v) Low metabolism due to the improvement of durability and adaptability;
(vi) A healthy environment for the occupants.

Graham (2003) emphasizes the required knowledge to relate building activities and ecosystems behaviour in order to create ecologically sustainable buildings. Because built and natural environment are infused, such knowledge includes the perception on how they interact regarding energy and materials flowing in earth cycles, and environmental effects.

Actually, in spite of the difficulties that can be pointed out for each case, the closing materials loop is consensual in the spectrum of Industrial and Construction Ecology, as being the main approach to waste minimization, and to reduction of natural resources depletion (Kibert, 2002; Kibert *et al.*, 2002).

However, main constraints on supply loop chains are the common challenges for industry in general (Geyer & Jackson, 2004). Such constraints may be identified as being the following:

(i) Downstream of products are in hands of the customers and not in the hands of the manufacturers;
(ii) Products are not typically designed for end-of-life value recovery.

In this context, characteristics of products disassembly for materials and components recovery are the core problem to be solved, in order to provide a continuous supply of high quality of recovered products to be used as raw materials in the production of new commodities.

2.2 *Closing materials loop: comparing industrial manufacturing and building construction concepts and practices*

The environmental ethics that emerged with the concept of Industrial Ecology produced a set of changes in the design and manufacturing processes in electronics, mechanics, and automotive industries. As a result, from the increasing depletion and costs of raw materials, and from the increasing production of waste, two primary objectives have been established in products manufacturing (Gungor & Gupta, 1999):

(i) Creating environmentally friendly products, the so called ‘green products’;
(ii) Developing strategies and techniques for products recovery and waste minimization.

Similar theoretical orientations and strategies for products recovery, such as conceiving products as decomposable items, were developed both in manufacturing industry and in building construction. However, output products from manufacturing and building construction exhibit different characteristics, and such properties highlight both similar and different constraints for materials and components recovery.

2.2.1 *The concept of ‘product’*

Consumption spectrum embraces a lot of different kinds of objects. These commodities vary in complexity, size, function and expected useful life. Electronic equipments, cars and buildings exhibit different characteristics, in particular those related with manufacturing, operating, maintaining, repairing, discarding, and recovering processes.

Krikke *et al.* (1998) proposed a disassembly tree model to describe a product, enhancing hierarchy and relationships between the parts. In this model, retrievable components are called assemblies (e.g. modules, parts, subparts) and are represented by a tree-like structure (see Figure 2.3). Each assembly is decomposed into subassemblies, except for the lowest level of the tree model. This product representation is limited to components product, and does not consider the material level, because materials do not represent an assembly. Materials are considered at components level if a recycling option is made.

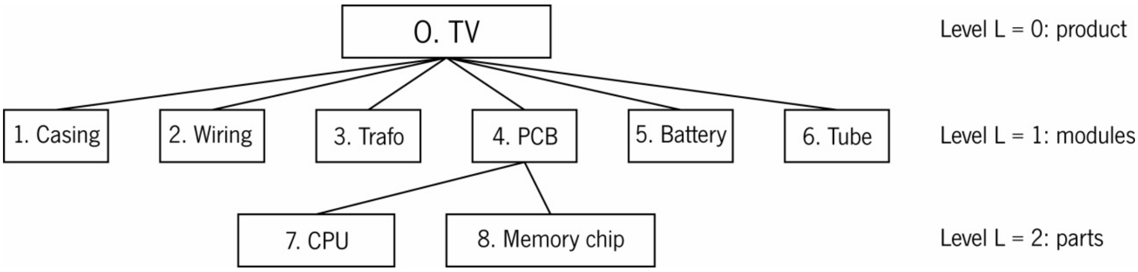


Figure 2.3. Disassembly tree of TV-X with nine assemblies and three levels (Krikke *et al.*, 1998).

A clear definition of what is a ‘product’ is proposed by Lambert & Gupta (2005). The authors define a product as being a representation of a particular functionality, understood as the ability to provide a service, which consists of an aggregation of several discrete parts. These parts are called components. Components are grouped on subassemblies or in modules, i.e. a set of components that performs a required function in order to accomplish the main function requirements.

One aspect not covered in this definition is also the material level, in which a material is shaped to give a form to the component, a form being the propriety that enables it to be joined with other components in place and used.

Thus, we may state that a product performs a demanded function, and it is an assembly, more or less complex, of groups of sub-assemblies and modules, which are made of components, which are, in turn, made from specific materials, in order to perform a required overall function.

In building construction the relationship between materials, components and sub-assemblies or modules may be identified as a hierarchy (see Table 2.2).

Table 2.2. Examples of hierarchical relationships between materials, components, and sub-assemblies or modules.

Material	Component	Sub-assembly or module
Clay	Brick Roof tile Ceramic tile	Wall Roof Floor
Steel	Sections	Load bearing structure Frames
Wood	Sections Panels	Load bearing structure Roof structure
Cement	Concrete Mortar	Load bearing structure Wall
Aluminium	Extruded profiles Plate	Windows frames Wall Roof
Glass	Plate	Windows

Therefore, the proposed definition of ‘product’ is valid for the all range of items, including buildings. Buildings are one of the most long life products across economic sectors (see Figure 2.4) and buildings exhibit particular characteristics when compared with other commodities (Kibert, 2003; OECD, 2003):

(i) It is not a factory made product, but incorporates factory made components;
(ii) An extended supply chain;
(iii) Discrepancy between owners and users;
(iv) Spatially fixed natures of products and production processes;
(v) Heterogeneity of buildings;
(vi) High capital cost;
(vii) Different precision level in manufacturing;
(viii) A longer lifespan, frequently unpredictable;
(ix) Designed by large teams of architects and engineers;
(x) Assembled on site by means of human and machine work;
(xi) Their quality is not extensively checked and tested;
(xii) Generally not identified with a producer label.

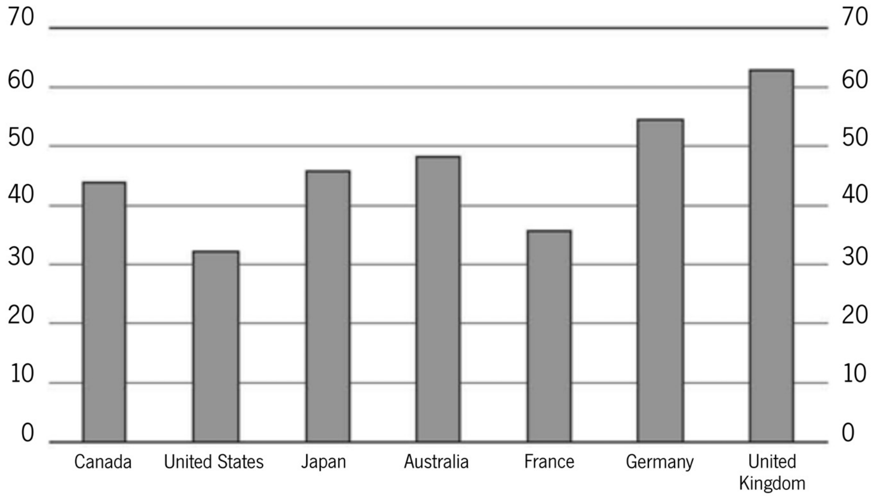


Figure 2.4. Estimated average service life of buildings and construction in selected OECD countries (years) (OECD, 2003).

These characteristics enhance that different challenges are supposed to be faced by the building industry, when compared with common durable goods manufacturing. However, actions for closing materials loop are grounded in the same principles.

2.2.2 *Product recovery strategies*

Product recovery aims to minimize the amount of waste sent to landfills and to maximize the amount of materials and components returned into the production systems through reuse, recycling, and remanufacturing processes. Supply loop strategies integrate traditional supply chains and end-of-life management of products recovery for recycling and reuse. Supply loop strategies fulfil two main criteria (Geyer & Jackson, 2004):

(i) To divert end-of-life products from landfill or incineration by collecting them for economic value recovery;
(ii) To replace primary resources by reprocessed end-of-life products.

A more sceptic perspective is brought by Ayres (1998) and Gungor & Gupta (1999) who stated that product recovery of both materials and components is carried out less by environmental concerns than because of:

(i) Hidden value of solid waste;
(ii) Market requirements;
(iii) Governmental regulations.

However, it must be emphasized that the main contribute of product recovery strategies for waste minimization, is that such strategies include waste management measures such as quality improvements and recycling (Jacobsen & Kristofferson, 2002).

In this framework, waste minimization practices would include the following actions:

(i) Dematerialization, i.e. to decrease raw materials inflows into and accumulation into the economy (Bartelmus, 2002);

(ii) Improvement of the efficiency of resources use, i.e. to prevent the wastage and degradation of these resources (Fatta & Moll, 2003);

(iii) Reduction of landfill and increase in materials recovery, i.e. closing materials loop by maximizing reuse and recycling industrial processes.

Production waste, end-of-life products and production by-products may have several solutions in the framework of waste minimization and waste treatment that comprise in general the following options:

(i) Source reduction;
(ii) In-process recycling;
(iii) On-site recycling;
(iv) Off-site recycling;
(v) Waste treatment to render the waste less hazardous;
(vi) Secure disposal;
(vii) Direct release to environment (landfill).

In this scenario, the manufacturing industry has to deal with product recovery and disposal strategies in a post-consumer phase. At that stage, takes place the assessment of recovery options, which are named as end-of-life scenarios, in order to identify the best solutions to meet environmental benchmarks. The categorization of these end-of-life scenarios may be more or less complex to comprise an adequate number of waste recovery options regarding the environmental requirements.

At this point, decision making on feasible end-of-life scenarios is of most importance to maximize the value of recovered materials and decisions may be taken from a number of perspectives, such as economic and environmental. For such purposes, tools for recovery level decision for end-of-life products were developed to enhance best recovery options such as value costs models based on products disassembly (Goggin & Browne, 2000).

Gungor & Gupta (1999) categorize material and product recovery options in the following process categories:

(i) Recycling: action performed to retrieve the material content of the obsolete products;

(ii) Remanufacturing: action performed to restore parts of products into like-new conditions.

Lambert (2003) points out end-of-life scenarios as a hierarchy, involving product repair, product remanufacturing, component reuse, materials recycling, and final disposal.

According to Thierry *et al.* (1995) and Lambert & Gupta (2005) material and product recovery is categorized in a larger set of options:

(i) Refurbishing: action performed to restore the functionality of end-of-life product, and these restored products are usually made available through second hand markets; Thierry et al. (1995) make a distinction between repair and refurbishment, being ‘repair’ as the action of bringing back used products to working properly, involving limited disassembly, fixings and replacing of parts out of order, and ‘refurbishment’ as the action of returning products to a specified quality level of functionality by disassembling it to module level, and involving inspection, repair and upgrade actions;

(ii) Remanufacturing: reconfiguration of products with components recovered from end-of-life products;

(iii) Reuse: employment of components and modules recovered from end-of-life products as spare parts; Thierry *et al.* (1995) refers to reuse as ‘cannibalization’;

(iv) Recycling: recovery of materials out of scrap from end-of-life products.

The European Directive for Waste Packaging (EU, 1994) also defines several forms of products recovery:

(i) Reuse: the use of the same product without essential changes in a new cycle;

(ii) Material recycling: the application of the material used for a new purpose without changing its chemical structure;

(iii) Chemical recycling: the change of the chemical structure of the material, where the resulting chemicals are used to produce a different material;

(iv) Recyling with energy recovery: the input of the material into a process that uses its energy content.

Reuse and recycling options may be further detailed by a set of sub options each, on the basis of the quality level, both at industrial manufacturing (Krikke *et al.*, 1998) and at building construction (Kibert & Chini, 2000) levels.

Krikke *et al.* (1998) decompose reuse processes in ‘upgrade’, ‘restore’, and ‘downgrade’. Further, they also decompose recycling in ‘high-grade’, ‘low-grade’ and ‘alternative’. Each level is characterized as follows:

(i) Reuse upgrade: the assembly is recovered at a higher level of quality than the initial performance;

(ii) Reuse restore: the assembly is recovered at the same quality level as originally;

(iii) Reuse downgrade: the assembly is recovered at a lower quality level than originally and becomes not suitable for their original market;

(iv) High-grade material recycling: original materials are recovered in their original quality;

(v) Low-grade material recycling: materials are recycled at a lower level of quality, it is often applied to indecomposable or contaminated materials;

(vi) Alternative material recycling: materials are recycled into entirely new materials, such as mixed plastics that are brought to original monomers to produce new kind of plastics.

Also Kibert & Chini (2000) presented a similar approach to recycling in the context of demolition and construction waste management, by dividing it into ‘up cycling’, ‘recycling’ and ‘down cycling’ (see Figure 2.5):

(i) Recycling at an up cycling level creates value added materials;

(ii) Recycling at a recycle level counts for the use of raw materials for a same equivalent purpose;

(iii) Recycling at a down cycling level means that raw materials are used in a lower value product.

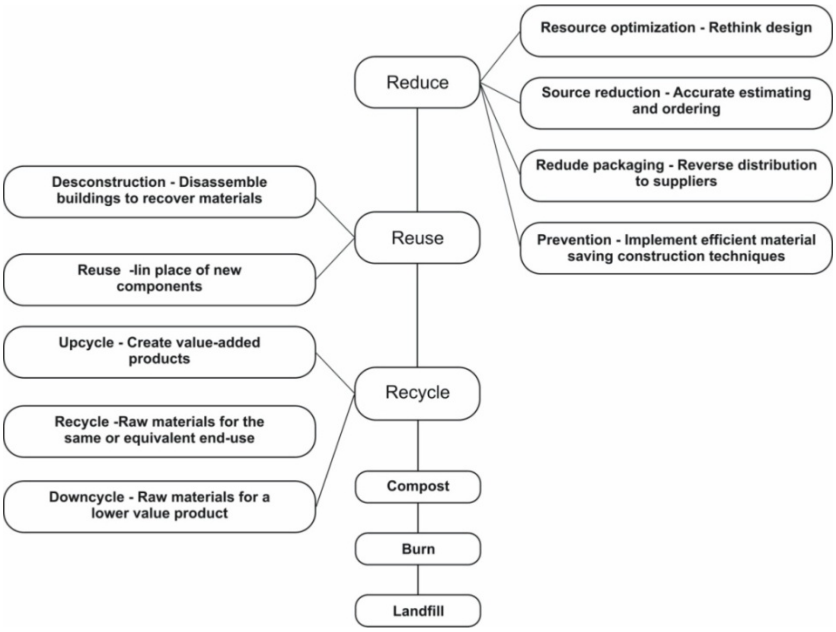


Figure 2.5. Waste management hierarchy for demolition and construction operations according to Kibert & Chini (2000).

An example of up cycle recycling is the use of wood chips as a raw material for the production of wood and phenol panels. Aggregates from concrete used in roads pavement layers are an example of recycling at a down cycle level.

Another approach distinguishing quality levels in product recovery options is presented by Lee *et al.* (2001), who define reuse, remanufacture, primary recycling (high grade), secondary recycling (low grade), incineration, and landfill.

An earlier hierarchical model of recycling levels in building construction was brought by Berge (1992), distinguishing the following degrees:

(i) Reuse: refers to the use of the whole component again within a same function and depends upon its lifespan;

(ii) Recycling: is dependent upon the purity of the materials and is achieved by smelting or crushing the component;

(iii) Energy recovery: refers to the production of energy by means of burning the product.

Macozoma (2002) also presents a hierarchy of the possible end use options for buildings, and materials and components:

(i) Building reuse: renovation, allocation, and adaptive reuse;
(ii) Component reuse: similar/different applications in situ or elsewhere, with high/low value use;
(iii) Material reuse: similar/different applications in situ or elsewhere;
(iv) Material recycling: upcycling, recycling, and downcycling;
(v) Incineration;
(vi) Immobilisation;
(vii) Landfill.

Gao *et al.* (2001) consider recycling within a broader definition. The authors define a recycled material as a material that can be remade or reused as a building material after building dismantling. In this definition, methods for processing reclaimed materials are classified into three types:

(i) Product recycle: process by which a product can be used again without changes in the form or nature of the material;
(ii) Material recycle: process by which a disassembled material is processed into a building material after being separated or collected;
(iii) Feedstock recycle: process by which a disassembled material is processed into feedstock to make a new building material.

Dorsthorst & Kowalczyk (2002) presented a global scheme for waste management in building construction (see Figure 2.6). Interactions between the building cycle and the waste cycle are here highlighted.

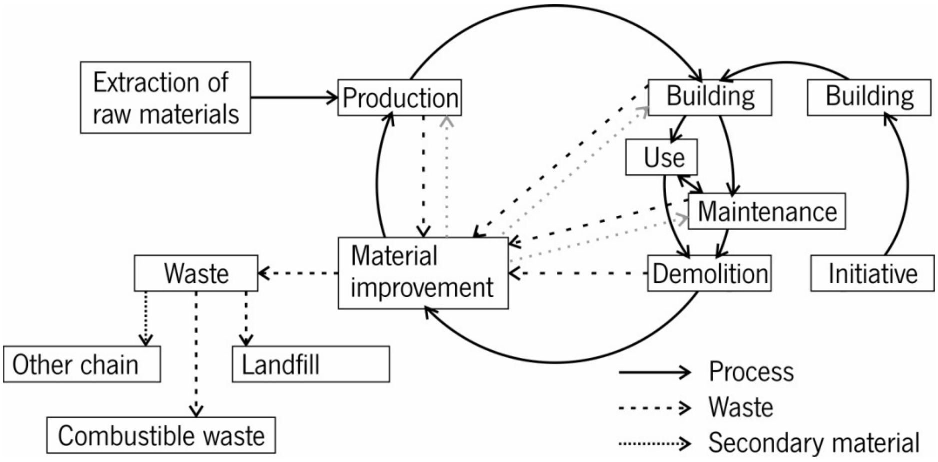


Figure 2.6. Waste management in building construction according to Dorsthorst & Kowalczik (2002).

Morgan & Stevenson (2005) proposed also an extensive hierarchy of levels in waste minimization in building construction:

- (i) Adaptive re-use of existing building;
- (ii) Design for adaptability and longevity of new buildings;
- (iii) Re-use of building elements/assemblies;
- (iv) Re-use of building components;
- (v) Recycling of materials;
- (vi) Reclamation of energy from building elements, components or materials;
- (vii) Landfill.

El-Haggar (2007) presents a simpler approach by defining reducing, reusing and recycling as end-of-life recovery alternatives:

- (i) Reducing: materials volume reduction at the source by changing producers and consumers practices;
- (ii) Reusing: continue using the product in its original or in a modified form, involving extended use of a product or use of a product for other purposes;
- (iii) Recycling: converting wastes to raw materials that can be reused to manufacture new products.

A relevant aspect on products recovery options is that it is related to different levels of the product disassembly:

(i) Refurbishing is performed at module level;

(ii) Reuse and remanufacturing are performed at component level;

(iii) Recycling is performed at material level, once identity and functionality of products, modules and components are lost.

Usually, a mix of recovery and disposal options is applied to an end-of-life product. Some parts can be reused, while others are recycled and other disposed off. The probability of this mixed options to occur increases with the complexity of the products.

This is especially true for buildings. Subassemblies can have an adaptive reuse such as structures and facades, and others can be reused in new or remodelled buildings, such as prefabricated load-bearing elements. Building components can also be refurbished such as air-cooling systems. Non separable elements such as masonry walls or floor ceramic pavements are usually recycled. Finally, non-separable materials due to chemical bonds and hazardous materials are disposed according to disposal regulations.

The recovery of material and products takes place in a process chain in which several actions are needed before recycle processing. In industrial manufacturing, these actions comprise (Gungor & Gupta 1999, Lambert & Gupta 2005):

(i) Collection: is a converging process to bring together dispersed products in a single product recovery facility;

(ii) Disassembly: a systematic method for separating a product into its different parts, such as modules, components and subassemblies, by non-destructive or semi destructive operations, according to a disassembly sequence, and it may be partial or complete;

(iii) Dismantling: a process in which destructive actions are performed to break down a part or the entire product;

(iv) Sorting: division of components and materials into clusters, which meet specific criteria on materials composition or components specifications;

(v) Shredding: reduction of materials and components into small pieces to increase materials homogeneity in order to enable separation processes;

(vi) Separation: division of shredder output according to materials composition using separation methods such as ‘magnetic separation’ and ‘eddy current separation’.

In the recovery of building materials, Hendriks *et al.* (2000) also identify similar processing methods at the end-of-life chain, grouping them into two main groups: ‘demolition’ and ‘separation’.

2.2.3 *Product recovery feasibility*

The overall feasibility of products recovery is constrained by the net profits for reuse, recycling and disposal. Thus, product and disposal options involve the assessment of its feasibility, by assessing both the disassembly level and the recovery and disposal options.

To define the most feasible recovery option or set of mixed recovery options, several aspects are to be considered according to Krikke *et al.* (1998):

(i) Technical feasibility: assessment of technical possibilities to perform the product recovery;
(ii) Commercial feasibility: assessment of business potential, such as exiting destination markets;
(iii) Ecological feasibility: assessment of ecological requirements, such as environmental regulations.

Technical feasibility assessment involves analyzing technical conditions of components and materials, processability of recovery, and identifying disassembling opportunities for components and materials. Technical feasibility assessment also considers processing materials properties to determine to what extent they can be recycled, and to identify complementary aspects: recognition of materials energetic value concerning materials incineration, shrinking properties concerning land filling, and hazardous contents that must be removed before recovery.

Commercial feasibility assessment aims to identify market revenues of products recovery. In order to define economic feasibility it is necessary to identify the potential markets with reference to the technological status of the overall product, the single components and the materials, so as to meet quality requirements. The potential markets are both internal, i.e. original manufacturers, and external, i.e. other manufacturers

Ecological feasibility assessment serves the purpose of identifying environmental constraints such as disposal bans and removal of hazardous contents. In this context, Extended Product Manufacturer responsibility must be considered also as an ecological requirement.

Lee *et al.* (2001) remark that the most appropriate end-of-life options depend on the nature of the components in the product. As guidelines for determining feasible end-of-life options, the following are suggested:

(i) If made of metal without any alloy, primary recycling is recommended, while if alloys are present then secondary recycling or landfill are appropriate;
(ii) If made of polymeric materials, primary recycling is recommended in first place, and secondary recycling and incineration with heat recovery are other alternatives;
(iii) If made of ceramic materials, secondary recycling or landfill are preferable;
(iv) If made of an elastomer or composite materials, secondary recycling and incineration are recommended;
(v) If it contains toxic or hazardous materials, special handling is required.

In building construction, Macozoma (2001) remarks that feasibility of materials and product recovery is constrained mainly by physical and economic factors.

As physical factors, the physical conditions of the building such as building type, status, location, neighbourhood context, degradation level, building materials quality, and access are pointed as influencing the feasibility of building deconstruction.

The economic factors that influence building deconstruction feasibility are related to the relationships between the availability of buildings with recoverable materials and the market demand for such kind of materials.

Regarding physical properties of buildings, Kibert *et al.* (2002) state that main difficulties constraining closing building materials loop are the facts that buildings do not exhibit disassembly properties, that most employed components are also not decomposable, and materials are often composites that disables recycling options. It is important to remark that despite composites not being easily recyclable, they might be quite easy to reuse, as for example high durability phenolic panels.

A example of materials recovery success is the Environmental Building (EB) built by the Building Research Establishment (BRE) in the UK (see Figure 2.7). The amount of recovered materials from the existing building demolition ranged 96 % by volume: brick work and concrete were crushed and used as hardcore under the new building, timber was recycled for furniture making, and steels roof trusses were sent for melting down and recycling (Thomas & Stevens, 1996).

Figure 2.7. Environmental Building (EB), Building Research Establishment (source: Thomas & Stevens, 1996).

Opportunities for recovery of building materials are strongly constrained by their quality as feedstock for recovery chain supplying. The quality of this feedstock is related with a set of parameters that includes:

(i) Level of physical and mechanical degradation;
(ii) Level of separation of building elements and materials;
(iii) Level of technical actuality;
(iv) Level of accordance with technical regulations and standards;
(v) Level of economic feasibility.

In spite of other constraints, feasibility of building materials and components recovery is highly dependent on implementing new design approaches such as Design for Disassembly. The availability of good quality salvaged materials and components may contribute for the economic importance of a new market based on materials recovery by feeding a supply-loop chain, and thus will contribute to reducing environmental impacts due to materials consumption.

2.3 *Design for Disassembly*

2.3.1 *Concepts and definition of Design for Disassembly*

The supply-loop approach stresses that recovery of materials and components is quite dependent on the earlier stages of products design and manufacturing, where materials are shaped and components are assembled. Minimization of environmental impacts and maximization of products recovery is linked with new design and manufacturing processes.

Environmental Conscious Manufacturing (ECM) is an approach to developing new processes for manufacturing products to meet environmental standards and to be easily recovered. The ECM strategy covers the entire life-cycle of a product, from conceptual design to final delivery, and the end-of-life disposal. According to Gungor & Gupta (1999), ECM consists of two key issues:

(i) To understand the life cycle of the products and its environmental impact at each stage of its life cycle;
(ii) To make better decisions during product design and manufacturing to keep the environmental attributes of the product at a desired level.

New tools are currently applied to product designing and manufacturing, such as Life Cycle Assessment (LCA), to support the broad approach of ECM, which allows a new understanding of product's environmental and health impacts during its life cycle. Furthermore, such integrative methodology benefits the decision-making processes in order to keep the environmental goals at the required level.

The ECM framework of products development is usually coined as Design for Environment (DfE) (Gungor & Gupta, 1999) and can be defined as the consideration of design performance with respect to environmental requirements over the entire life cycle.

DfE can be broken in a set of different assessments along the product life-cycle stages, such as energy conservation, minimizing the discharge of hazardous by-products, materials conservation, ease of disassembly, and recyclability of components and materials (Fiksel & Wapman, 1994; Fiksel *et al.* 1996).

Therefore, DfE also embraces the extended producer responsibility of Original Equipment Manufacturers (OEMs). In this context, one of the main problems that manufacturers have to deal with is to recognize to what extent it would be possible and feasible for products to be recovered. Krikke *et al.* (1998) proposes the determination of optimal Product Recovery and Disposal (PRD) as strategies to support decision-making.

Within a closing materials supply-loop approach, DfE is supported by a set of design frameworks regarding the end-of-life scenarios of a product. Such frameworks include product recovery strategies such as at the design stage of products:

(i) ‘Design for Recycling’;
(ii) ‘Design for Remanufacturing’;
(iii) ‘Design for Disassembly’.

It is possible to point out interdependences between the three design strategies, as Design for Disassembly (DfD) assists Design for Recycling and Design for Remanufacturing to increase the recovery efficiency by allowing selective separation of parts and materials (Gungor & Gupta, 1999).

DfD assists also a broad environmental approach labelled as Design for Life Cycle. Design for Life Cycle considers all phases of the product life in the design stage, such as production, consumption, maintenance, and discharge. In the conceptual phase of a product, the design of adequate assembly systems that allows dismantling processes should be included, once the recovery opportunities are constrained strongly by the design of the product itself (Lambert & Gupta, 2005).

DfD focuses on how to design easily disassembled products in order to guarantee that the components and materials can be easily and economically separated, and ultimately to facilitate their reuse, recycling or neutralisation if toxic or dangerous.

DfD must be considered at the design stage and includes principles such as the following (Vezzoli & Manzini, 2008):

(i) Reduce and facilitate operations of disassembly and separation;
(ii) Engage reversible joining systems;
(iii) Engage permanent joining systems that can be easily opened;
(iv) Co-design special technologies and features for crushing separation.

There are several reasons for the implementation of DfD in product’s development (Lambert, 1997; Das *et al.*, 2000; Gungor & Gupta, 2001; Vezzoli & Manzini, 2008):

(i) To extend the product lifespan (easy maintenance, repair, updating);
(ii) To recover valuable and reusable parts or subassemblies;
(iii) To separate in order to facilitate the downstream material recovery processes;
(iv) To remove hazardous or toxic materials;
(v) To increase the purity of the remainder of product;

(vi) To remanufacture the product for another useful life;
(vii) To decrease the amount of residues to be sent to landfills;
(viii) To provide accessibility to other parts that should be removed;
(ix) To achieve environmental friendly manufacturing standards, by increasing the use of recycled materials in manufacturing new ones.

A distinction must be made between disassembly levels and recovery and disposal options because if disassembly is not feasible, then there is no option to be considered for recovery and disposal scenarios. Thus, a product's recovery strategy is integrative and consists of the following aspects:

(i) A product analysis and determination of disassembly schemes based on the product composition and relationships between the parts and materials qualities;
(ii) A definition of the optimal choice from recovery and disposal options for the different parts of the disassembled product, by applying both environmental and net costs criteria.

If this problem has been faced in industrial manufacturing, such as electronic equipments or vehicles, by adapting the assembling lines to the new technical requirements and challenges for using the available resources in a more efficient manner (Gungor & Gupta, 2002), building construction has a broader and more complex challenge to face due to buildings characteristics.

Traditionally, a building is a unique product designed for a customer and is a response to a given set of requirements that varies according to building owner, function, number of occupants, climatic conditions, aesthetic considerations, and available construction technologies. Furthermore, buildings were not and are not commonly conceived to be disassembled, and often incorporate non decomposable components and composite materials. Such conditions show to what extent building construction faces a set of different problems regarding disassembly practices, when compared with common standardized manufactured products.

Standardization of buildings and standardization of sub-assemblies may be an answer for disassembly practices implementation within the built environment. Examples have been tried by houses manufacturing industries (see Figure 2.8). However, due to unique design requirements, such practices are not diffused among practitioners and building owners, and are in most cases not possible to implement. While, standardization of building systems has been applied to several kinds of buildings, commercial standardization of entire buildings is only feasible at small scale buildings production.

Another aspect to be considered is that standardization of buildings is not really related to environmental concerns, it is rather related to the development of cheaper and easily deliverable building solutions, by saving onsite construction costs and time. Although such buildings may exhibit disassembly opportunities they are not usually conceived for disassembly purposes or with environmental commitments regarding waste minimization goals.

Figure 2.8. Hive modular B-Line (source: http://www.hivemodular.com).

DfD should not be understood as the reverse of Design for Assembly (DfA). DfA is the set of formal analysis procedures to assess the suitability of design manufacture and assembly, and it is usually considered at the earliest stage of the design before the options become a commitment at the production stage (Abdullah *et al.*, 2003). Assembly costs, i.e. labour, in manufacturing are reported as being in a range between 20-70% of total cost of production with an average of 45% (Mo *et al.*, 1999; Abdullah *et al.*, 2003). Thus, in recent years, industry has put a big effort on reducing assembling costs by developing methodologies for assembling planning.

The main goal of DfA is to facilitate assembly by designing the product throughout by applying the following principles (Mo *et al.*, 1999):

(i) Simplifying the composition of the product by reducing the number of parts and reducing the variation of material types;
(ii) Facilitating the assembly procedures by designing a product that makes easier the assembly operations and enhance opportunities of parallel assemblies;
(iii) Simplifying the assembly operations by designing for fitting and insertions, simplifying assembly adjustments;
(iv) Evaluating the assemblability by estimating constraints and estimating assembly costs.

According to Lambert (2003), seven main characteristics distinguishes ‘Disassembly’ practices from ‘Assembly’ ones:

(i) Disassembly is often not performed to its full extent, and in some cases incomplete disassemble is the optimal solution;
(ii) Assembly processes are often not completely reversible;
(iii) The value added in disassembly is not as high as revenue obtained in assembly optimization;
(iv) Uncertainty with regard to the quality of the components;
(v) Uncertainty in the market supply of discharged products, both qualitative and quantitative;
(vi) A great number of supplied products is often present for disassembly;
(vii) Mainly carried out by human work instead of automated processes.

Therefore, disassembly may be defined as the process of physically separating a product into its parts or subassembly parts by a systematic procedure that allows reusable, recyclable, non-recyclable, and hazardous subassemblies to be selectively separated (Gungor & Gupta, 1999). Disassembly may be classified as non-destructive by systematic removal of the product constituents from an assembly, and as destructive by separating materials from an assembly in order to sort and reclaim each material type for recycling (Gupta & Mclean, 1996).

Studies in disassembly theory have several purposes and are embedded in broader frameworks, such as Industrial Ecology, Design for Environment or Design for Life Cycle (Lambert, 2003). These purposes are the following:

(i) Optimal repair and maintenance;
(ii) Development of tools for assembly optimization;
(iii) Design and optimization of disassembly lines and processes;
(iv) Optimum product design regarding the product's end-of-life options, which is called usually as Design for Disassembly (DfD).

2.3.2 *Analysis of disassemblability and disassembly planning of products*

The recognition of a hidden value of solid waste and the EPR are the main causes of special attention given to products disassembly, in order to avoid long term costs in product management. Therefore, disassembly actions aim to achieve a recovery feature in which the profitable value and environmental requirements are kept at the desired levels.

Although entire disassembly of products seems to give the best environmental opportunities by reducing impacts from waste disposal, in particular those with hazardous parts, disassembly is very dependent on operational costs and relies on the market value of disassembled components.

Operational costs of disassembly tasks are highly dependent on the disassembly level and disassembly sequencing (Ron & Penev, 1995; Gungor & Gupta, 1999):

(i) The disassembly levelling determines how far to disassemble in order to keep the profit reasonable;
(ii) The disassembly sequencing determines the optimal way in which components should be removed to minimize labour and time costs, in order to obtain the best cost/benefit ratio.

The approach to optimal disassembly levelling enhanced the need to develop new tools for quantitative assessment. Disassembly levelling has been represented by several models, in order to understand how the product may be decomposed and the level of disassembly's feasibility.

To find the most efficient way to perform disassembly tasks has become a main issue for disassembly success. Initial studies on disassembly planning focused on repair and maintenance procedures. However, emphasis on sustainable production stimulated the research on disassembly and the emphasis shifted towards products recovery opportunities (Lambert, 1999). Thus, disassembly planning aims to find optimal or mean responses to materials and components recovery, as well as to minimize disassembly costs, in order to obtain the best cost/benefit ratio.

The challenge of disassembly planning is to identify the optimal disassembly sequence under a given set of constraints, in which the number of options for disassembly sequences increases exponentially as the number of components increases in a product (Gupta & Mclean, 1996). Other challenge for disassembly planning is to find a method that fits the broad spectrum of products to be disassembled (Wiendahl *et al.*, 1999).

The uncertainty about disassembly optimal procedures increases with products complexity: weight, size, materials composition, configuration, and age. This is quite true for the deconstruction of existing buildings. The absence of information is critical both for optimal disassembly sequencing and for disassembly planning and scheduling.

Disassembly process of representation usually employs disassembly precedence graphs, disassembly trees, state diagrams, and AND/OR graphs (Lambert & Gupta, 2005).

In the manufacturing industry, optimum disassembly sequences have been studied by applying mathematical programming methods. Within such approaches, also several software systems have been developed to assist disassembly planning in Design for Disassembly of manufacturing products.

Earlier approaches to assembly/disassembly planning were brought by Homem de Mello & Sanderson (1986, 1988, 1990, 1991, 1991a) which proposed the application of AND/OR graphs to represent all the possible assembly plans of a given product. For such representation an algorithm was developed for generating all possible assembly sequences. In these models, disassembly sequences are considered as the reversed ones of the corresponding assembly sequences.

Later approaches such as Erdos *et al.* (2001) extended the application of AND/OR graphs to the automatic generation of disassembly and recovery sequences. Also, Lambert (1997, 1999, 2001, 2002, 2003a, 2006, 2007) presents a set of models for disassembly planning and costs evaluation based in the information condensed both in the connection diagram and in the set of precedence relations of a product, to generate automatically a disassembly sequence using AND/OR or heuristic graphs.

Gungor & Gupta (1997) proposed a methodology to evaluate different disassembly strategies by means of a heuristic disassembly sequence generation, which gives a near optimum disassembly sequence for a product. The heuristic model analyses precedence relationships of the product components, disassembly time of each component, disassembly directions and joint types of the components. Later, Gungor & Gupta (2001) proposed a disassembly sequence tool using a branch-and-bound algorithm to automatically generate disassembly sequence plans for product recycling and remanufacturing, by analysing precedence relationships.

Johnson & Wang (1998) also proposed to use heuristics to evaluate the economics of disassembly operations and materials recovery, in order to improve the efficiency of the disassembly planning process and to generate an optimal disassembly sequence which maximizes profit.

A graph-based heuristic approach is proposed by Kuo (2000) and Kuo *et al.* (2000) for disassembly analysis, by applying disassembly analysis to generate a disassembly tree. The model was developed to support design of products by giving information on disassemblability and recyclability. Later, Kuo (2006) developed the model in order to integrate life-cycle analysis in disassembly trees analysis.

Moore *et al.* (1998, 1998a) proposed a model to disassembly process planning based on an algorithm which automatically generates a disassembly Petri net from a geometrically precedence matrix, that uses a mathematical modelling language to describe systems by means of a graph representation. The disassembly Petri net can generate all feasible disassembly plans and costs functions are used to determine the optimal disassembly sequence. As an alternative, heuristic methods can also be applied to generate near-optimal disassembly plans. This approach was developed further by Moore *et al.* (2001) by integrating analysis of products with AND/OR precedence relationships

A software tool for disassembly planning was developed by Kanai *et al.* (1999) using Petri net graphs to generate a graphic representation of the disassembly planning model. The model integrates four levels of graph analysis: a configuration graph of sub-assemblies, a connection graph between parts or materials, a process graph of disassembly and materials recovery tasks (e.g. shredding and sorting), and a retrieval condition graph.

Also Gadh *et al.* (1998) proposed software for evaluation of CAD models of product designs by evaluating disassembling techniques for maintenance such as selective disassembly and destructive disassembly. The software assesses the easiness of product disassembly for maintenance, the disassembly sequencing to maintain a selected set of components, and the disassembly cost for maintenance.

Dini *et al.* (2001) presented a software system for the optimization of the recycling process, to be integrated with CAD. The software assists on the best disassembly plan on the basis of the maximum profit achievable from the recycling of components, which is calculated according to the information stored in the database (see Figure 2.9). The system automatically detects the subassemblies of the products, and automatically generates all the feasible disassembly sequences.

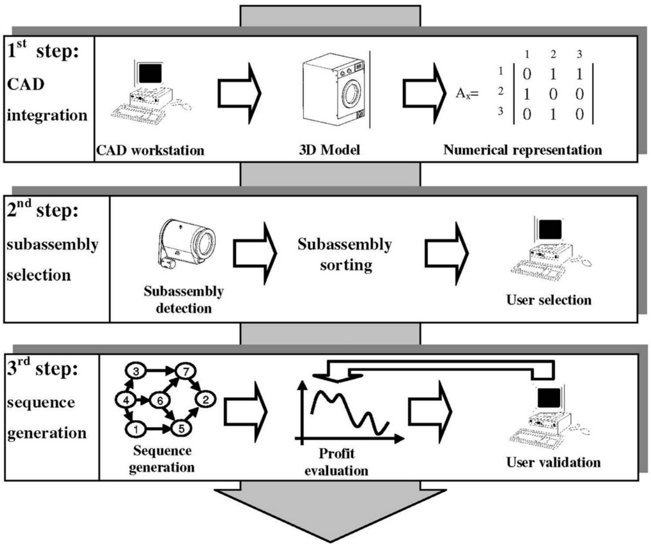


Figure 2.9. Framework of the disassembly planning system (Dini *et al.*, 2001).

A disassembly matrix is proposed by Huang & Huang (2002) to improve computer-aided disassembly planning tools in order to evaluate potential products for ease of disassembly at the design stage. The method employs Boolean operations to create all of the possible disassembly sequences and directions for components in a tree diagram.

Disassembly was also analysed through time estimation tools to evaluate disassembly efficiency by identifying weaknesses in the product's design and to improve it accordingly (Kroll & Carver, 1999).

In spite of the extensive research developed by the electronics and robotics industry on disassembly planning sequences as a fundamental part of the DfD framework, the construction industry does not seem to be sensitive to such development. Apart the statement of principles for DfD of buildings, which is also coined as 'Design for Deconstruction', whose list may be shorter or longer according to different authors (Crowther, 2001, 2003; Morgan & Stevenson, 2005; Clapham *et al.*, 2008), the most innovative approaches to DfD had been the proposal of tools for the evaluation of the amount of waste generated by dismantling operations (Touran *et al.*, 2003; Guy & Ohlsen, 2003), the costs associated with deconstruction (Seemann *et al.*, 2002), the disassemblability of buildings (Durmisevic *et al.*, 2003), and the recycling potential of buildings by means of materials and components recovery (Thormark, 2001; Gao *et al.*, 2001). In fact, there is none or no significant research undergoing on disassembly planning sequences in building construction and though it would be an interesting field to be developed, if focused on the complexity of buildings as products.

2.4 *Design for Disassembly/Deconstruction (DfD) and building construction*

Historically, buildings and materials have been reused and it is also quite common to find examples of reuse of materials in new buildings, which were recovered from old structures demolishing, especially stone masonry, steel sections, facing bricks, and wood beams.

However, few buildings arise from the history of architecture as examples of ancient practices of disassembling for products reuse and recycling. Those examples are expressions of cultural contexts, such as the Ise Shrine, in Japan, where the inner sanctum has been dismantled and rebuilt every 20 years over the past 1300 years, by reusing parts of the dismantled shrine in the construction of new shrines over the country.

Other examples are ultimately design experiences carried out by architectural researchers, such as the Office Building XX designed by the Dutch architect Jouke Post (see Figure 2.10), that was conceived to be disassembled after a 20 years lifespan. The building was conceived as a flexible unit that would stay adaptable during the building's use phase. The solution was based on an open building system with several independent systems to provide a high level of flexibility and demountability (van Dijk *et al.*, 2000).

Figure 2.10. Office Building XX designed by the Dutch architect Jouke Post (Leupen, 2005).

Practical lessons on assembly/disassembly come also from temporary and portable buildings, and from pre-fabricated buildings. Temporary buildings have been used from the beginnings of humankind, with the appearance of the first shelter transportable by nomadic prehistoric peoples (Kronenburg, 1995, 1996). Temporary buildings such as theatre stages or exhibition pavilions are also classical examples of buildings which were designed with disassembly properties (see Figure 2.11).

Although portable and pre-fabricated buildings exhibit a lot of the DfD principles, such buildings are not indeed related to a DfD approach, as they are conceived for easy transport, handling and assembly, but not necessarily for being disassembled at the end-of-life.

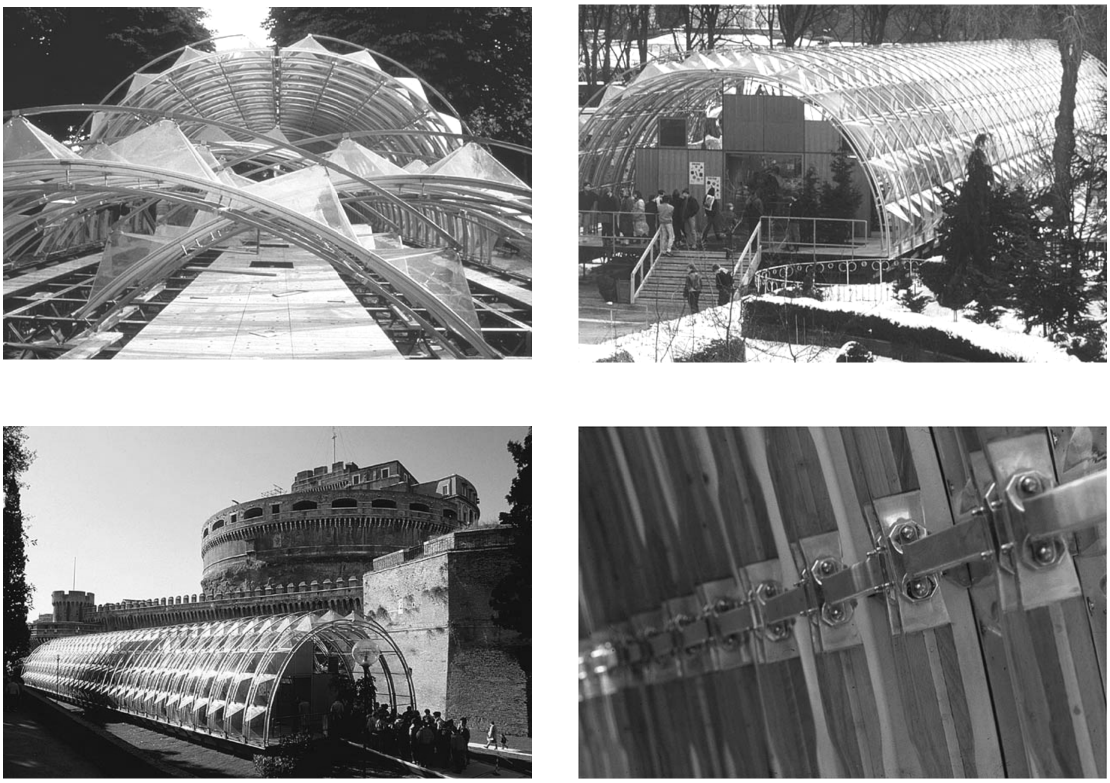


Figure 2.11. Renzo Piano IBM travelling exhibition pavilion (Source: http://www.freewebs.com).

As stated before, such solutions were not really developed in a waste minimization framework. However, it is possible to argue that in a certain way temporary and portable buildings represent a broad approach both to DfA and to DfD.

Current building deconstruction experiences and activities brought most of the knowledge on constraints to building materials recovery and enhanced the role of the design stage to provide partial or entire building disassembly opportunities in the future.

Challenges faced by deconstruction are significant (Kibert & Chini, 2000; Kibert, 2003, 2005):

(i) Buildings are custom-designed and custom-built by several intervenient;
(ii) Existing buildings have not been designed for disassembly;
(iii) Materials and components have a long lifetime;
(iv) Building systems are often replaced or updated throughout building lifespan;
(v) Building components have not been design for disassembly;
(vi) Tools for deconstructing existing buildings often do not exist;
(vii) Disposal costs for demolition waste are frequently low;
(viii) Dismantling of buildings requires additional time;

(ix) Re-certification of used components is not often possible;

(x) Building codes often do not address the reuse of building components;

(xi) The economic and environmental benefits are not well-established.

A first approach to DfD in building construction was suggested by Berge (1992) by presenting a set of principles coined as Assembly for Disassembly (ADISA) by which the design of direct re-use of building materials would allow the reduction of the amount of discarded materials and component into landfills.

The most extensive work on building deconstruction and Design for Deconstruction of buildings was produced by CIB Task Group 39 – Deconstruction between the years 2000 and 2005. Several guides on Design for Disassembly were also published, such as Morgan & Stevenson (2005) and Guy & Ciarimboli (2006).

There are not relevant approaches to include DfD in building codes. A first approach has been adopted by the Canadian Standards Association, by establishing a Technical Committee on Sustainable Buildings, with the task of developing national standards to advance the design, construction, and maintenance of buildings in a sustainable manner (Clapham *et al.*, 2008). Among these standards, a 'National Standard on the Design for Disassembly and Adaptability' is under development.

2.4.1 *Design for Disassembly/Deconstruction (DfD): principles and practices*

According to previous experiences in deconstruction of existing buildings, sets of principles to be included in DfD have been developed to guide designers along the design stage of the building. Such principles are based mainly on connections definition, type of materials to be employed, hierarchy between components, sub-assemblies and assemblies, and information management regarding future disassembly.

Berge (1992) suggested a set of few principles for an approach that he called as Assembly for Disassembly (ADISA), in order to establish some guidelines for designers:

(i) Separate layers: this principle is based on Brandt's model of building layers (Brandt, 1994), in order to efficiently reuse both the whole building and its components;

(ii) Possibilities for disassembling each layer: any single components within each layer should be easily disassembled, in order to be reused or sent for recycling or energy recovery;

(iii) Use of standardized monomaterial components: simplicity of components composition and shape allows easy reuse and recycling processes.

Crowther (2001, 2003) proposed an extensive set of detailed principles that have to be attended in DfD:

(i) Use recycled and recyclable materials;
(ii) Minimise the number of different types of materials;
(iii) Avoid toxic and hazardous materials;
(iv) Avoid composite materials and make inseparable subassemblies from the same material;
(v) Avoid secondary finishes to materials;
(vi) Provide standard and permanent identification of material types;
(vii) Minimise the number of different types of components;
(viii) Use mechanical connections rather than chemical ones;
(ix) Use an open building system where parts of the building are more freely interchangeable and less unique to one application;
(x) Use modular design;
(xi) Use construction technologies that are compatible with standard, simple, and ‘low tech’ building practice and common tools;
(xii) Separate the structure from the cladding, internal walls, and services;
(xiii) Provide access to all parts of the building and to all components;
(xiv) Make components and materials of a size that suits the intended means of handling;
(xv) Provide means of handling and locating components during the assembly and disassembly procedure;
(xvi) Provide realistic tolerances to allow for manoeuvring during disassembly;
(xvii) Use a minimum number of fasteners or connectors;
(xviii) Use a minimum number of different types of fasteners or connectors;
(xix) Design joints and connectors to withstand repeated use;
(xx) Allow for parallel disassembly rather than sequential disassembly;
(xxi) Provide permanent identification of component type;

(xxii) Use a structural grid;

(xxiii) Use prefabricated subassemblies and a system of mass production;

(xxiv) Use lightweight materials and components;

(xxv) Permanently identify points of disassembly;

(xxvi) Provide spare parts and on-site storage for them;

(xxvii) Sustain all information on the building construction systems and assembly and disassembly procedures.

Further discussion on these principles may be accessed in Crowther (2003).

Sassi (2006) also suggests a set of recommendations for designing for dismantling, reuse and recycling:

(i) Information: provide identification of points of disassembly, components, and materials, and also identification of materials and component types.

(ii) Access: provide easy and safe access to disassembly elements and fixings;

(iii) Dismantling process: simplify fixing systems and provide disassembly means by not using very complex tools;

(iv) Hazards: avoid toxic materials and employ components suitable for safe handling;

(v) Time: minimize number of parts, fixings, and types of fixings, allowing parallel disassembly;

(vi) Reprocessing: avoid non-recyclable materials and minimize the number or components;

(vii) Durability: avoid fragile material and employ joints and components for repeated use;

Clapham *et al.* (2008) established a set of principles for guidance of the Canadian National Standard on Design for Disassembly and Adaptability for Buildings:

(i) Versatility;

(ii) Convertibility;

(iii) Expandability;

(iv) Documentation of disassembly information;

(v) Durability;

(vi) Exposed and reversible connections;
(vii) Independence;
(viii) Inherent finishes;
(ix) Recyclability;
(x) Refurbishability;
(xi) Remanufacturability;
(xii) Reusability;
(xiii) Simplicity.

Despite the reasonability of the proposed principles as guidelines for building designers, they cannot assist DfD as an evaluation tool, and give feedbacks for design improvement. Tools to support decision making in DfD would enhance the recovery opportunities and environmental effectiveness of a design solution or in comparing different building solutions at the design stage.

2.4.2 *Constraints to disassembly/deconstruction*

In Design for Disassembly/Deconstruction approaches, two main factors have to be taken in account for:

(i) Flexibility: service life hierarchy and functional independence of materials and components;
(ii) Connections: between components and sub-assemblies.

Considering such factors at design stage enables disassembly sequencing and technical feasibility of materials and components dismantling.

(1) Flexibility

In conventional buildings, components and subassemblies are closely related and the sum of the parts acts as one single structure, and therefore replacement of components and materials have several consequences on adjacent elements. Relations of dependence enable easily repair and maintenance, and ultimately materials recovery.

In fact, a building is a structure composed by several functional levels where materials and components establish hierarchical relationships according to their position and function, and according to their forecasted Service Life. By enhancing independent relationships between components and functions, it is possible to adjust configuration design of buildings in order to improve the quality of recovered materials, or to optimize the building design to adjust to a given end-of-life scenario. This means flexibility.

Flexibility is a key aspect to be considered in DfD (Hurley *et al.*, 2002; Durmisevic & Brouwer, 2002; Macozoma, 2002). According to Durmisevic & Brouwer (2002) and Durmisevic & Iersel (2003), functional aspects and technical life of building materials interact for the definition of possible End-of Life Scenarios. This approach is called as life cycle co-ordination and is an essential aspect for DfD. The idea is in accordance with the shearing layers of change proposed by Brandt (1994) and to service-life planning because it involves the consideration of the performance of a building over its predicted life (Flanagan & Jewell, 2005; Triunus & Sjostrom, 2005).

This approach indicates that decomposable buildings exhibit a structure of components and subassemblies that determine the behaviour or function of the total building, determining the level of flexibility. Materials and components with short service lives should be more flexible while materials with longer service lives may be placed in a more fixed manner (see Figure 2.12). Such an approach stresses the fact that configuration design is the key for building disassembly.

Macozoma (2002) also enhances the concept of flexibility in DfD to ensure adaptive use and easy component and material disassembly for reuse and recycling. Flexibility is considered as a balance between durability, i.e. adjusting service lives of components to building's lifespan, and adaptability, i.e. accommodating changes in requirements of the physical environment.

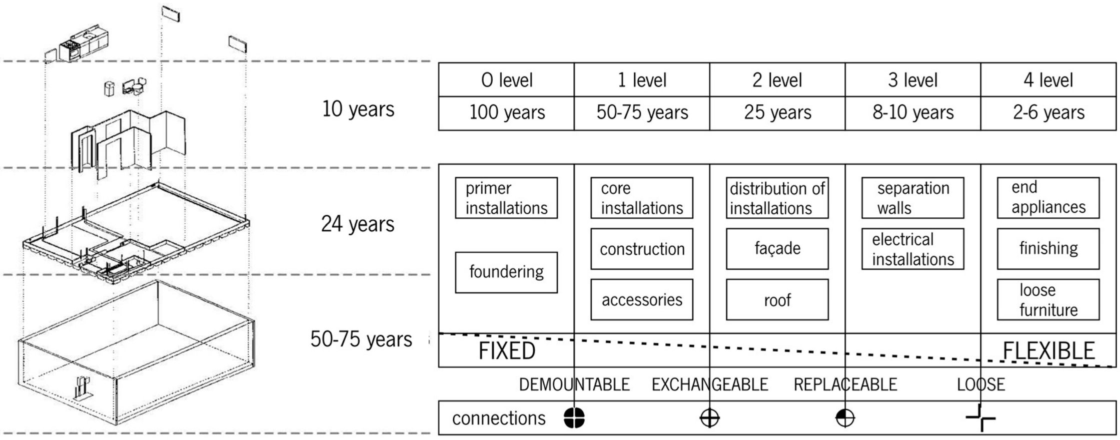


Figure 2.12. Systematization of building systems and their interfaces according to their service lives (Durmisevic & Brouwer, 2002).

Furthermore, functional aspects should be included in life-cycle coordination. Different functions on buildings have different behaviours, and therefore criteria of independence and exchangeability should be applied (Durmisevic *et al.*, 2003): independence as the quality of building components to be recognized and separated as individual parts, and exchangeability as the potential of a component to be disassembled. A component can be dismantled if it is an independent part, not performing more than one function, and if the interfaces with other parts are demountable.

Principles for DfD proposed by Durmisevic & Brouwer (2002) outline characteristics of independence (see Figure 2.13):

(i) Functional decomposition: separation between different functions;
(ii) Clustering/systematisation: clustering of building elements which act as an independent building subsystem;
(iii) Open hierarchy: recognition and separation of building layers with different service lives and functions;
(iv) Base element specification: definition of the base element which integrates all surrounding elements of that cluster;
(v) Assembly sequences: recognition of the type of assembly sequence employed; i.e. parallel or sequential assembly;
(vi) Interface geometry: degree of freedom between components;
(vii) Type of connection: definition of connection type that could be integral, accessory or filed connections.

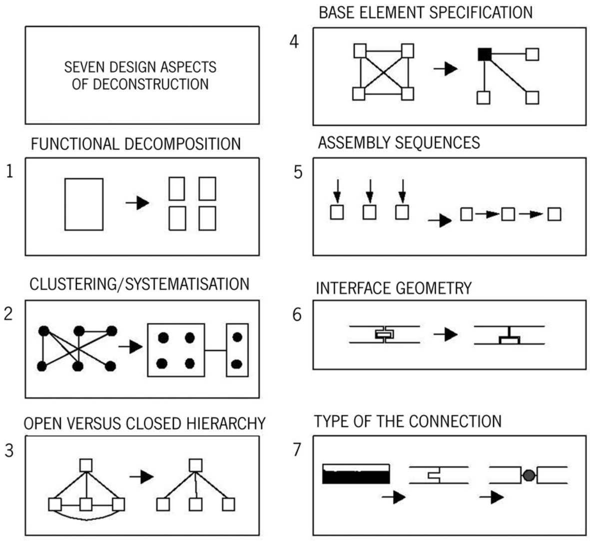


Figure 2.13. Aspects of structural transformation according to Durmisevic & Brouwer (2002).

(2) Type of connections

Development and specification of disassemblable joints and fixtures is crucial for the success of deconstruction activities, once connections play a key role in determining the disassemblability of the product (Hesselbach & Kuhn, 1998; Hurley *et al.*, 2002; Gungor, 2006). For ease of disassembly, a selection of fasteners that are easily unfastened is therefore an important decision in products design.

In engineering assembly processes of materials and components, connections or joinings may be classified according to three types of forces: mechanical, chemical and physical (Brandon & Kaplan, 1997; Messler Jr., 2004). These three types of forces lead to the following three main types of connections according to Messler Jr. (2004): mechanical joining, adhesive bonding and welding connections (see Figure 2.14).

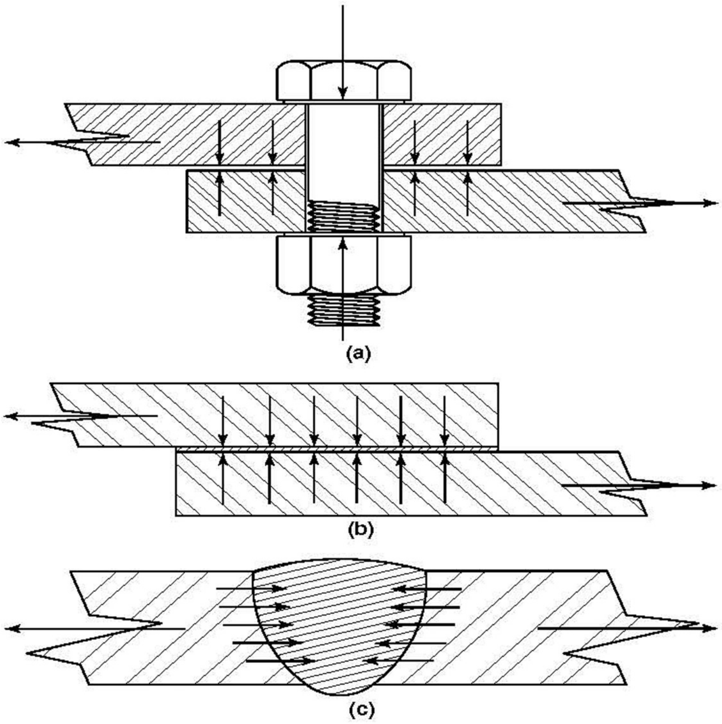


Figure 2.14. Different types of joining and type of forces used: (a) mechanical joining, (b) adhesive bonding, and (c) welding (Messler Jr., 2004).

Mechanical joining methods use localized point-attachment processes, in which the joint between two or more elements is provided by a third element such as a nail, a rivet, a screw or a bolt. This kind of joints enables ease of assembly and disassembly. Mechanical joints depend on residual tensile stresses in the attachment to hold the elements in compression (Brandon & Kaplan, 1997; Messler Jr., 2004).

Adhesive joining methods employ a bonding agent capable of holding together the elements to be joined, by means of the attraction force arising from chemical origins. The adhesive or bonding agent must be chemically compatible with and chemically bondable with the adherent surfaces (Messler Jr., 2004). Adhesives include glues and cement or cementitious materials.

Welding joining methods employ physical forces to unit two or more materials through the application of heat or pressure to allow the bonding to occur. Welding joining may be used in metals, thermoplastic polymers, and glasses. Employed welds must be produced between equal types or classes of materials (Messler Jr., 2004). Welding joining may be subdivided in brazing and soldering methods which require a filler material. In brazing methods, bonding is achieved by heating the surfaces in the presence of a molten filler. In soldering methods, bonding is achieved by employing a filler that melts and substrates that do not melt.

Lambert & Gupta (2005) point a set of thirteen connections types in relation to their different characteristics, present a more complex approach to connections characterization for assembly and disassembly of industrial products, regarding:

(i) The ability to non-destructively release the fasteners;
(ii) The amount of force necessary to undo the connections;
(iii) The restriction in movement;
(iv) The type of fastener used.

Based on these parameters, the following types of connections were defined (Lambert & Gupta 2005):

(i) Mating connections;
(ii) Bundling connections;
(iii) Spring connections;
(iv) Screw connections, bolt and nut connections;
(v) Cotter pin, staple, and related connections;
(vi) Snap fit connections;
(vii) Press fit connections;
(viii) Rivet connections;
(ix) Seam fold connections,

(x) Glues and seal connections;
(xi) Solder connections;
(xii) Weld connections;
(xiii) Mould Connections.

Gungor (2006) classifies connectors in several groups according to their mechanical properties as following:

(i) Discrete fasteners: independent of the parts to be assembled; cause no damages to the assembled parts; able to join parts made of different materials; reusable; may be a single unit or consist of multiple elements, such as screws, bolts, nuts, washers, springs and bundlers;
(ii) Integral attachments: integrated into the assembled parts, do not require assembly tools, such as locators, locks, compliant, and snap-fits;
(iii) Adhesive bonding: join parts with different types of glues by means of adhesion, chemical reactions and phase transition mechanisms, and their use may complicate the disassembly process;
(iv) Energy bonding: join parts by employing a joint that is melted or plasticized in order to form a bond using an external energy source, such as soldering, blazing, welding and moulding;
(v) Other connectors: those who do not fall in the previous categories, such as seaming, crimping, zippers, and Velcro.

Another approach to connections classification is brought by Durmisevic & Brouwer (2002) that classify connections according to their interface:

(i) Direct or integral connections: the geometry of a component edge forms a complete connection, that can be overlapped, or interlocked if the edges exhibit different geometries;
(ii) Indirect or accessory connections: an additional part is used to form a connection, such as screws or nails;
(iii) Filed connections: two components are filed with chemical material, such as welded connections.

Regarding the classification of joining types in mechanical joining, adhesive bonding, and welding, the first type exhibits easy disassembly properties when compared with the others. In mechanical joining, the fastener may be also reused as long as it keeps its shape and functionality. Adhesive bonding and welding disables the disassembly of the parts. In a simplified approach, all the connections may be classified as 'open' connections, i.e. mechanical joining, and 'closed' connections, i.e. adhesive bonding and welding.

2.4.3 *Evaluating buildings disassembly*

Building environmental assessment methods are tools to improve buildings performance in order to achieve a set of environmental goals. Different tools have different relevance according to use in context and assessment target. Life Cycle Assessment (LCA) tools such as the Athena Environmental Impact Estimator (developed by the Athena Institute) and BRE's Environmental assessment (BREEAM) and Envest (developed by the UK Building Research Establishment - BRE) are used to evaluate materials or strategic design options from the point of view of environmental impacts. Other methodologies relate to scoring performance by aggregating points and derivation of weights, regarding a set of pre-established parameters of eco-efficiency. Methods such as BREEAM (developed by the UK Building Research Establishment - BRE) LEED (operated by the US green Building Council), and the SBTool (developed by the International Institute for Sustainable Building and Environment - IISBE) have been in place for a long time to assist the evaluation of the environmental performance of buildings. Emerging methods or new tools for building environmental assessment are enhancing the dialogue between various members of design teams in order to establish a common ground (Cole, 2005), which is quite important for DfD practices.

Concerning the development of tools to assist DfD there is currently no relevant framework. Tools for DfD are limited to evaluation methods of building design according to a set of parameters to assess disassemblability level, and recycling potential of recoverable materials by means of disassembly. No tools for disassembly planning for application in building construction were found in the literature.

Dorsthorst & Kowalczyk (2002) proposed a tool labelled BELCANTO, to support the choice between different design strategies such as Design for Adaptability, Design for Deconstruction, and Design for Dismantling (see Figure 2.15). The output of BELCANTO would be at least the environmental loads of a building product, but it also integrates the life cycle costs of possible End of Life Scenarios.

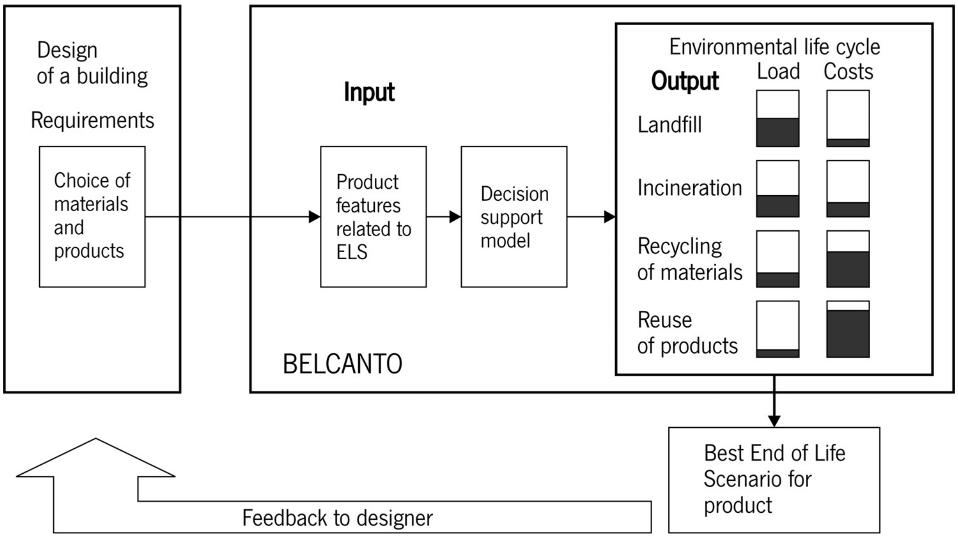


Figure 2.15. BELCANTO framework (Dorsthorst & Kowalczyk, 2002).

A classification of decomposable structures is proposed by Durmisevic & Brouwer (2002), by evaluating aspects of structural transformation (see Figure 2.13). The classification is made according to three types of building structures:

(i) Fixed structures: maximal integration and dependence between building components, due to no service life hierarchical relations, sequential assembly; integral joint types, and use of chemical connections;

(ii) Partly decomposable: combination of fixed and flexible elements, in which fixed elements are those with high durability and flexible elements are those frequently exposed to change;

(iii) Totally decomposable: totally demountable building structures, which can be relocated or reused elsewhere or in different combinations or be recycled.

This classification is developed by Durmisevic *et al.* (2003) by defining the disassembly potential as the ability of a building's structure to be selectively dismantled with the purpose of reuse and recycling of materials and components. A framework for the development of a knowledge model for assessing disassembly potential of structures is proposed. The model proposes three categories for the classification of disassembly potential, based on the performance of independence and exchangeability indicators:

(i) Category 1: low disassembly potential – both indicators have less than 30% of their best values;

(ii) Category 2: medium disassembly potential - both indicators have between 30% and 70% of their best values;

(iii) Category 3: high disassembly potential - both indicators have more than 70% of their best values.

In the framework of the model, the two indicators of independence and exchangeability rely on the specification of building configuration aspects, such as hierarchy, materials, and connections (see Figure 2.16).

The disassembly potential is evaluated by grading a set of fuzzy variables from zero to one, zero being the worst impact and one the best impact on disassembly. The fuzzy variables are organized to evaluate functional decomposition, life cycle coordination, relational pattern, systematization, assembly, geometry, and connections.

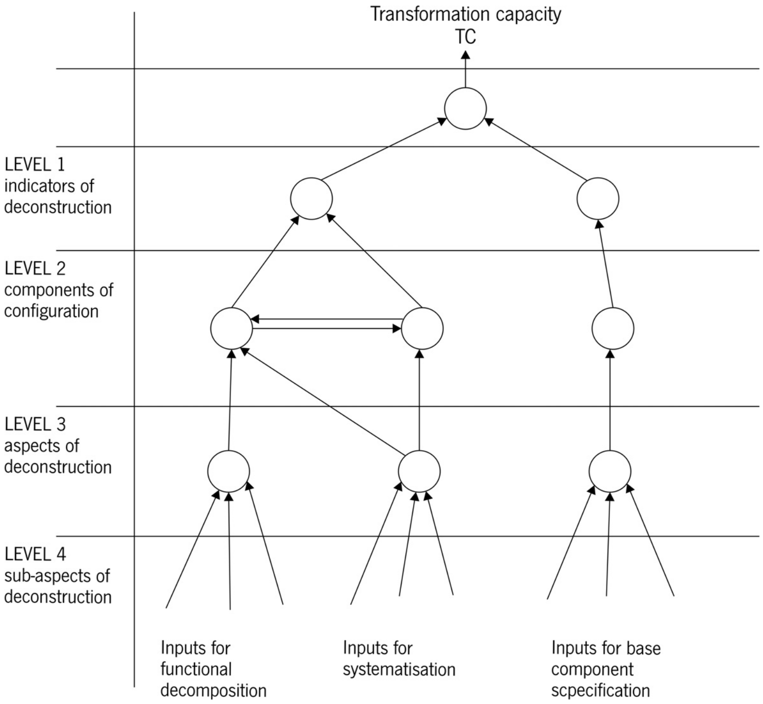


Figure 2.16. Simplified knowledge model for the assessment of disassembly potential and transformation capacity (Durmisevic *et al.*, 2003).

DfD is also a key factor to improve the building's recycling potential framework proposed by Thormark (2000, 2001, 2001 a, 2001 b, 2002, 2006). The recycling potential, Rpot expresses how much of all embodied energy and natural resources used in a building or a building element is possible to recover after demolition by means of recycling processes.

The recycling potential assessment may be mainly used in the planning of a demolition by assessing the potential benefits in order to plan the building deconstruction, and in the design process in order to design buildings with a low environmental impact by enhancing their recycling potential.

The Recycling Potential model uses Embodied Energy in the building for comparison with energy savings by recycling waste, which were assumed as the embodied energy for the material that the recycled material is supposed to substitute minus the energy of recycling processes. The conservation of natural resources was defined as the amount of material that recycled materials were assumed to substitute. In the model, reuse, recycling, and combustion with heat are considered as end-of-life scenarios.

As results of the Recycling Potential model are dependent on the properties of reclaimed materials components, such as quality, heat content, recycling and reuse opportunities, the index can be a good measure of the disassembly potential of buildings in a quantitative approach.

Gao *et al.* (2001) proposed a method to evaluate the energy impacts of recycling disassembly material in residential buildings, by analysing the potential energy savings when the building materials and products are manufactured from recycled materials. The energy consumption of recycled materials evaluates three types of processing: product recycle, material recycle, and feedstock recycle. Results of the application showed that aluminium and steel products were the key products to be recycled, that reuse of building structural elements offers much more potential energy savings than recycling, and recycling of renewable resources such as wood which shows low potential savings.

A generic approach that may be applied also to buildings is suggested by Villalba *et al.* (2004) by emphasizing the feasibility of products disassembly. The proposed Recyclablity Index (*R*) is a tool to determine if disassembly design allows for material recovery, by measuring the ability of a material to regain its valued properties through a recycling process. Therefore, the index is calculated based on the difference between the economic value of the reclaimed material and the economic value gained by recycling it, by means of estimating the percentage of the product that exhibits a high recycling potential.

2.5 *Discussion*

Due to environmental conscious manufacturing and waste minimization strategies, disassembly of end-of-life products plays a key role on the reduction of natural resource consumption, throughout reducing the environmental impacts generated by resource harvesting and the discarding of obsolete products. Reclamation of outdated products is then a crucial aspect for waste minimization. However, in general, end-of-life products are not designed for being recovered, and a shift in products design and manufacturing is crucial to achieve the desired environmental benchmarks. Disassembly is now an important component of the life cycle of products to be taken into account for achieving materials recovery efficiency.

Efforts on buildings are usually put on time and costs reduction without taking into consideration what will happen after they reach their end of use, and therefore buildings were not and are not usually conceived to be dismantled, and ultimately for materials and components recovery.

An example of a new environmental vision regarding products end-of-life comes from the electronics and automotive industries. Due to Extended Producer Responsibility legislation, manufacturing industries are focusing on the life cycle of products, and especially on their disassembling properties to enable materials and components recovery. Such an approach allows adding an economic and environmental value to recovered products.

Currently, in building construction the problem with the great amount of waste generated by building demolitions overcomes the future problems with the buildings that are currently built. The traditional demolition processes are being replaced gradually by partial dismantling or by the so called building deconstruction activities. This is especially true in countries with high rates of building materials recovery such as the Netherlands or Japan.

As a feasible alternative to traditional demolishing practices, the building deconstruction approach meets the concept of waste minimization, and is related with the concept of natural metabolism processes, enhancing reuse and recycle opportunities. However, efficiency of building dismantling, both for economic and environmental feasibility, is dependent on a shift in the manner buildings are conceived and built: to move from compact buildings to dissassemblabe structures by means of Design for Disassembly/Deconstruction practices.

Kibert (2002) compares DfD practices to the design of natural systems and their ability in effective recycling of materials that circulate in ecological systems, which means that it is not possible to achieve completely the goals of sustainability in construction without a building deconstruction approach. In fact, DfD provides the conditions by which the building materials and components loop is closed.

By definition, DfD assists products development in order to improve materials and components disassembly and to maximize the amount and the quality of reclaimed materials for reuse and recycling processes.

Therefore, DfD has been widely developed by industrial manufacturers to meet environmental and legislation requirements, and thus products have been developed in manners different from what they used to be. Tools for assembly/disassembly analysis and programming have been developed in order to maximize quality of recovered materials, and efficiency in disassembling products and components, especially by time and work savings.

In the manufacturing industry, especially in electronic and automotive industries, qualitative and quantitative tools have been developed to assist the disassembly of products by generating optimal disassembly sequences and to assist products design and development. The application of mathematical tools is a valuable approach to understand disassembly, enhancing future constraints at the design stage.

In building construction, DfD is seldom applied as a design strategy. Complexity of the whole building construction, with many actors on the field, does not enable a common discourse regarding environmental goals. Until now, efforts on materials recovery have been applied in what existing buildings concerns.

DfD in buildings have to integrate analytical tools both at the building disassembly sequences and planning, but also tools to analyse the environmental benefits of materials recovery. Such tools would inform the building design process in order to improve solutions by identifying constraints such as flexibility and connections aspects, and by perceiving the possible recovery alternatives.

To include disassembly planning in buildings design framework, by means of applying DfD principles, seems to be in need of future developments. Such developments would enhance the organizational level of the building as a flexible and interchangeable system in order to allow disassembly.

Environmental approaches are also important to enhance the environmental advantages of materials recovery. In order to analyse the level of buildings disassemblablity it is not enough to understand the environmental benefits of materials recovery. Analysis of the recycling potential has been proposed as tools to assist DfD by means of comparing embodied energy of materials and recycled ones. However, embodied energy does not enhance the work of nature by including it in the environmental value of materials.

Hence a broader approach that would include both nature and human work embodied in a product would enhance the effectiveness of materials recovery that underlies the efficiency of the recovery and recycling processes. By analysing the real net benefits of materials recovery at the design stage, the environmental goals of building disassembly would be assessed and integrated in decision making.

CHAPTER 3

MAIN FACTORS INFLUENCING MATERIALS RECOVERY

Among all the factors that influence the assessment of materials recovery processes, service life management, materials recovery rates, and end-of-life scenarios requires a more detailed analysis. Variations in these topics may lead to different recovery results, both for the quantity and the quality of salvaged building materials.

Data on these topics are dispersed in the literature and several approaches are usually considered by different authors. In order to clarify the state of the art, a survey on these subjects is presented, gathering information on theoretical approaches, practices, reference values for Forecast Service Life and Recovery Rates, and references on End-of-Life Scenarios for different building materials.

3.1 *Service Life of materials and components*

The estimation of Service Life of materials and components became a useful approach to manage their maintenance and replacement in order to minimize waste produced during the life span of a building, and to maximize building waste recovery.

Research on prediction of Durability and Service Life of materials, components, and buildings, covers estimation methodologies and tools, as well as generic estimations for buildings and materials or components based on building system configuration, such as load bearing structure, façades, roof, infrastructures, and interior partition.

However, there is no consensus on definitions and standard values for the Service Life of materials, or concerning the best approach or methodology to be used.

3.1.1 *Definitions for Durability and Service Life*

With reference to the concepts of Durability and Service Life, several different definitions are adopted by different national and international documents, such as the European Construction Products Directive (EC, 2004), the European Organisation for Technical Approvals (EOTA, 1999, 1999a), and the International Standard ISO 15868-1:2000 (Marteinsson, 2005; AI, 2006).

The European Construction Directive 89/10/6EEC adopted a set of definitions regarding Durability of construction products and materials. In the revised Guidance Paper F – Durability and the Construction Products Directive, definitions for Durability and Working Life (i.e. Service Life) are given (EC, 2004):

Durability of a product: the ability of a product to maintain its required performance over a given or long time, under the influence of foreseeable actions. (...) Durability is thus dependent on the intended use of the product as a whole and its service conditions.

The definitions adopted in the Construction Products Directive distinguish between Working Life of works and Working Life of a product.

Working Life (works): the period of time during which the performance of the works will be maintained at a level compatible with the fulfilment of the Essential Requirements.

Working Life (product): the period of time during which the performance of a product will be maintained at a level that enables a properly designed and executed works to fulfil the Essential Requirements (i.e. the essential characteristics of a product meet or exceed minimum acceptable values, without incurring major costs for repair or replacement). The working life of a product depends upon its inherent durability and normal maintenance.

The European Organisation for Technical Approvals (EOTA) adopted the same definitions in the guidance documents (EOTA, 1999, 1999a) for the development of European Technical Guidelines on the subject of Assessment and /or Prediction of Working Life of products.

The International Standard for service life planning of Buildings, ISO 15686-1:2000 Buildings and Construction Assets, Service Life Planning Part 1: General Principles presents definitions and the framework for a methodology on Service Life estimation. In the standard ISO 15686-1:2000, Service Life is defined as (Marteinsson, 2005; AI, 2006):

Period of time after installation during which a building or its parts meets or exceeds the performance requirements.

Concerning a definition for Service Life, ISO standard distinguishes between Estimated Service Life, Predicted Service Life, and Forecast Service Life, depending on the degree of empirical versus evidence knowledge (AI, 2006):

Estimated Service Life: service life that a building or parts of a building would be expected to have in a set of specific in-use conditions, calculated by adjusting the reference in-use conditions in terms of materials, design, environment, use and maintenance.

Predicted Service Life: service life predicted from recorded performance over time.

Forecast Service Life: service life based on either predicted service life or estimated service life.

In the same standard ISO, the term Durability is defined not as an inherent material property because it is dependent on several extrinsic factors (Marteinsson, 2005; Brischke *et al.*, 2006, AI, 2006).

Durability is the capability of a building or its parts to perform its required function over a specified period of time under the influence of the agents anticipated in service.

Estimation of Service Life has the purpose of determining the moment when the material will no longer be able to perform its function. However, End-of-Service Life may not be exclusively related to a physical decay that can be extended or not by means of repairing actions.

Moser (2004) describes the End-of-Service Life of a component as the point in time when the foreseen function is no longer fulfilled, according to a set of properties, notably:

(i) Safety: integrity of the component is maintained at the required level of safety;
(ii) Function: the required function is fulfilled;
(iii) Appearance: the expected appearance is maintained.

From the above definitions, a distinction can be made between Obsolescence and Durability. Durability is related to the physical performance of a material or component according to a set of physical conditions and required functions. Obsolescence is a wide concept and covers subjective constraints, such as aesthetic, technical upgrades and new regulations that are not covered by Durability definitions. According to Iselin & Lemer (1993), Obsolescence may be defined as following:

The condition of being antiquated, old fashioned, or out of date, resulting when there is a change in the requirements or expectations regarding the shelter, comfort, profitability, or other dimension of performance that a building or building systems is expected to provide. Obsolescence may occur because of functional, economic, technical, or social and cultural change.

Thus, Obsolescence does not necessarily mean a dysfunctional or broken item, although these conditions may underscore obsolescence.

Ashworth (1996) also distinguishes between physical deterioration and obsolescence. Obsolescence constraints may be of technological, functional, economic, social, or legal nature.

Due to obsolescence, the replacement of materials and components may occur before their physical decay. Depending on the fulfilment of technical requirements, these materials and components may be suitable for reuse or upgrade. Materials replaced due to their physical decay are not usually suitable for direct reuse, being more suitable for recycling processes.

Thus, the definition of Service Life might be extended in a way to cover both 'physical life' and Obsolescence, as the period of time over which a building, material or component accomplishes both physical performance requirements and overall expectations regarding its use.

However, it is not possible to predict subjective constraints of Obsolescence. Expectations are not measurable and tested in the same way as physical performance and decay processes are, for which it is possible to employ methods using previous experiences and testing, as well as analytical models.

3.1.2 *Methods for Service Life prediction*

Methods for Service Life prediction of buildings, components, and materials rely on the characterisation of physical properties of materials and components under the action of degradation agents over time. Service Life prediction tools are generally applied in Service Life Design, Life Cycle Assessment, Whole Life Appraisal (Flanagan & Jewell, 2005), Engineering Reliability (Yang, 2007), Reliability Centred Maintenance (Bloom, 2006), and Cost Benefit Analysis frameworks.

Methods for Service Life prediction can be divided in two main approaches (Hovde, 2004):

(i) Probabilistic approach;
(ii) Deterministic approach.

Thus, methods for service life prediction may be assessed by empirical models based on experience and tests results (i.e. deterministic), and by analytical models based on degradation mechanisms and kinetics (i.e. probabilistic).

The probabilistic methods quantify uncertainties by using analytical tools. In these methods, degradation is assumed to be a stochastic function governed by random variables (Moser, 2004). Markov Models, Monte Carlo Models and density distributions methods are employed in probabilistic methods (Moser, 2004; Marteinsson, 2005). These types of models deal with several dependent variables, based on a large amount of information about the variables and how they interrelate.

Deterministic methods apply specific evaluation factors to establish Service Life of materials and components. The so called ‘Factor Method’ was adopted by the International Standard for service life planning of buildings ISO 15686-2:2001 Buildings and Construction Assets, Service Life Planning Part 2: Service Life Prediction Procedures.

According with ISO 15686-2:2001, the Factor Method estimates the Service Life of a material or component based on a Reference Service Life and a set of modifying factors that relate to the specific conditions of the case study (Hovde, 2004). Reference Service Life is the service life expected for a certain set of in-use conditions. Specific factors or variables that affect service life are the following:

(i) Factor A: quality of the components;
(ii) Factor B: design level;
(iii) Factor C: work execution level;
(iv) Factor D: indoor environment;
(v) Factor E: outdoor environment;
(vi) Factor F: in-use conditions;
(vii) Factor G: maintenance level.

According to ISO 15686-1, the following formula expresses the Factor Method:

$$ESLC = RSLC \text{ x } Factor\ A \text{ x } Factor\ B \text{ x } factor\ C \text{ x } Factor\ D \text{ x } Factor\ E \text{ x } Factor\ F \text{ x } Factor\ G$$

Where:

ESLC: Estimated Service Life of Component

and RSLC: Reference Service Life of Component

Reference Service Life is based on data provided by means of the service life prediction methodology or tests carried out, on previous experience or observation of similar components, on building codes, on literature, and on certificates of durability produced by certified boards. Procedures for reference lives are described in standard ISO 15686-8:2008 Buildings and Construction Assets, Service Life Planning Part 8: Service Life Prediction Procedures.

Modifying factors are based on tests or experiences from previous use, according to known degradation effects and environments, and represent the deviation from the assumed conditions for which the reference service life was estimated (Jernberg *et al.*, 2004). The factors should be adapted for each material considered, and factor weight must also be adapted regarding environmental constraints such as climatic influences (Brischke *et al.*; 2006).

Factors lower than unit reduce the estimated service life and factors higher than unit increase the estimated service life. The reliability of the method depends on the accuracy of the input data.

The European Organisation for Technical Approvals adopted similar methodology as guidance for working groups on the subject of Assessment and Prediction of Working Life of products (EOTA, 1999a).

Moser (2004) proposed a so called Engineering Design Method by combining both specific factors to be evaluated, and mathematical relations such as probability design functions. However, due to variability in degradation processes, prediction of Service Life is not as exact science as it is desired.

From a survey of the available literature, it is possible to group Service Life estimations in two kinds of approaches:

(i) Building sub-systems and large assemblies level;
(ii) Material/component level.

The first approach is based approach on an overall vision of the sub-systems or parts of a building such as structure, external envelope, services, and finishes (Brandt, 1994; Amato & Eaton, 1997; Durmisevic & Dorsthorst, 2002). This approach does not distinguish materials and products, and references for durability are given as generic reference values for the sub-systems.

The second approach is a material/component oriented, based on the intrinsic durability of a single material or component. This approach is in accordance with methods for Service Life prediction, both deterministic and probabilistic.

3.1.3 *Building sub-systems and large assemblies level*

Several authors and technical documents refer to Service Life as a generic period in which a building sub-system or a large-assembly fulfils the overall user requirements.

Brandt (1994) proposed the concept of hierarchical building layers (see Figure 3.1).

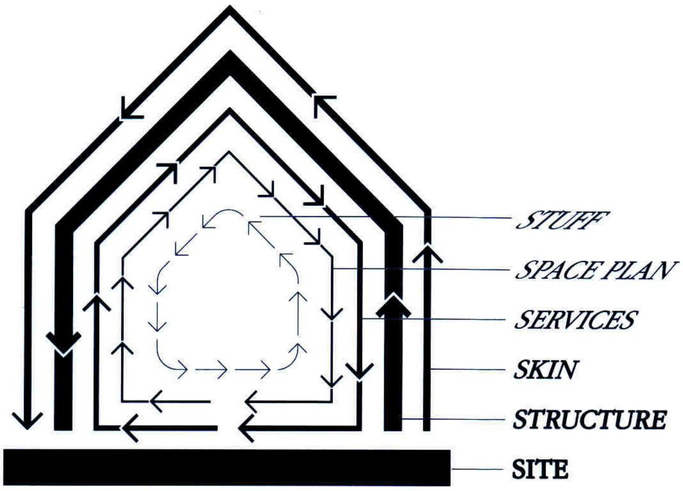


Figure 3.1. Shearing layers of change (Brandt, 1994).

Based on the observation of buildings changes and their adaptive use, Brandt (1994) integrates both objective (physical decay) and subjective (space function, outdated systems, fashion and technology) constraints to establish generic references for Service Life of building layers (see Table 3.1).

Table 3.1. Service life for shearing layers of change according to Brandt (1994).

Layers of change	Service Life (years)
Site	Eternal
Structure	30 - 300
Skin	20
Services	7 – 15
Space plan	Commercial space: 3 Residential space: 30
Stuff	-

To build according to the hierarchy of the ‘Shearing Layers of Change’, would maximize Service Life of materials and components, enhancing maintenance and adaptation conditions. As a result, it would be possible to reduce the amount of waste due to maintenance, repair, upgrade, and refurbishment operations.

A similar approach is brought by Amato & Eaton (1997) using the term 'Lifetime' instead of 'Service Life'. According to the authors, different parts of commercial buildings have the following lifetimes:

(i) Structural system: 50 to 150 years;
(ii) External envelope: 20 to 60 years;
(iii) Services: 10 to 20 years;
(iv) Finishes: 5 to 15 years.

Also Durmisevic & Dorsthorst (2002) define generic timeframes for Service Life of different parts of a building, by stating the following service life of the main building functions in an optimal spatial flexibility for a 75 years' service life of a dwelling:

(i) Load bearing: 75 years;
(ii) V. Communication: 75 years;
(iii) Cladding: 50 years;
(iv) Servicing: 30 years;
(v) Partitioning: 5-8 years;
(vi) Outlets: 2-5 years.

In the guidance documents of the European Organisation for Technical Approvals (EOTA, 1999) Service Life, or Working Life, is also assumed as a generic timeframe. Service Life management is assumed to be the best relation between the Life span of the building or parts of the buildings, and the expected Working Life in relation with the level of repairability of products (see Table 3.2).

Table 3.2. Assumed Service Life of works and construction products to be used by the European Organisation for Technical Approvals (EOTA, 1999).

Assumed life of works (years)		Working life of construction products to be assumed (years)		
		Category		
Category	Years	Repairable or easily repairable	Repairable or replaceable with some more efforts	Lifelong
Short	10	10	10	10
Medium	25	10	25	25
Normal	50	10	25	50
Long	100	10	25	100

3.1.4 *Material/component level*

Studies on Service Life estimation for materials and components are scarce. A survey was made in order to establish reference Service Lives for several materials and components (see Table 3.3.). Values are dispersed in the literature and they must be assumed as generic orientations, because it is not always possible to distinguish between 'Estimated Service Life' and 'Predicted Service Life' as defined according to the Factor Method framework. Thus, the generic term 'Forecast Service Life' was adopted in this study to express the average durability of materials and components.

Different Forecast Service Lives were found for a same material. This is due to specific factors taken in consideration, such as functional and climatic factors.

Concrete and Wood seem to be the materials with major significant research on Durability, with employment of Service Life estimation methods.

A survey on technical data provided by construction products manufacturers was not effective in providing data. In general, technical sheets do not make references to Estimated Service Life or Reference Service Life for a given product.

The values collected from bibliography are only generic references. As for some materials significant differences for the Forecast Service were pointed, a previous assessment of specific conditions of use should be applied.

Table 3.3. Forecast Service Life for selected building materials and components.

Material	Component/service	Forecast Service life (years)	Reference sources
Aluminium	Door and window frames	30	Buranakarn (1998)
	Siding	80	Lippiatt (2007)
	Roofing	35	Piper (2004)
	Exterior doors	30	Piper (2004)
Asphalt	Roofing shingles	20	Piper (2004) and Lippiatt (2007)
Asphalt (Hot-mix)	Pavement (parking)	>50	Lippiatt (2007)
Cement	Mortar	30	Craven *et al.* (1994)
	Mortar	>60	Anderson *et al.* (2002)
	Stucco external finishes	100	Lippiatt (2007)
	Fibre cement shingles	45	Lippiatt (2007)
	Concrete paving	30	Lippiatt (2007)
Ceramic	Ceramic tiles (floor and wall finishing)	30	Craven *et al.* (1994)
	Ceramic tiles (walls)	25-30	Piper (2004)
	Ceramic tiles (flooring)	50	Lippiatt (2007)
	Ceramic tiles (flooring)	25-30	Piper (2004)
	Stoneware: water closets	20	Piper (2004)
	Stoneware: urinals	20	Piper (2004)
	Stoneware: sinks	15-20	Piper (2004)
	Sanitarian: tubs / showers	20-25	Piper (2004)
Clay	Hollow bricks masonry	40-45	Liska (1998)
	Brick masonry	= building	Piper (2004)
	Facing bricks	>100	Lippiatt (2007)
	Tiles	30	Buranakarn (1998)
	Roofing tiles	>100	Lippiatt (2007)
Concrete	Columns and beams	150	Craven *et al.* (1994)
	Concrete slabs, walls, beams, and columns	>100	Lippiatt (2007)
	Walls	>60	Marteinsson (2003)
Copper	Roofing	40	Piper (2004)
	Pipes	35-50	Piper (2004)
Cork	Flooring	>50	Lippiatt (2007)
Glass	Flat glass	60	Craven *et al.* (1994)
	Fibreglass	>50	Lippiatt (2007)
Glass asphalt	Pavement	5	Chiu *et al.* (2008)

Table 3.3. Continued.

Material	Component/service	Forecast Service life (years)	Reference sources
Gypsum	Plasterboard	75	Lippiatt (2007)
	Plasterboard	>60	Anderson *et al.* (2002)
	Plasterboard (walls and ceilings)	20-30	Piper (2004)
	Traditional interior plaster	30-50	Piper (2004)
Lime	Plaster	60	Craven *et al.* (1994)
Paints	Plaster finishing	15	Craven *et al.* (1994)
	Plaster finishing	5	Anderson *et al.* (2002)
	Interior latex paint	4	Lippiatt (2007)
Plastics : HDPE	Pipes	30	Goodship (2001)
		20	Piper (2004)
	Plastic lumber	<50	Goodship (2001)
Plastics : Melamine-formaldehyde	Laminate surfaces	<10	Goodship (2001)
Plastics : Nylon	Carpet	11-15	Lippiatt (2007)
Plastics : Polyamide (PA)	Carpets	10	Goodship (2001)
Plastics :Polystyrene (PU)	Cladding out insulation (including finishing)	50	Lippiatt (2007)
Plastics : Polyurethane (PU)	Foam insulation	<10	Goodship (2001)
	Roof spraying	20	Piper (2004)
Plastics : PVC	Window frame	>20	Bernard *et al.* (200o)
	Window frame	25	Thompson (2005)
	Flooring	5	Goodship (2001)
	Flooring	2-10	Bernard *et al.* (2000)
	Flooring	20-35	Piper. (2004)
	Flooring tiles	40	Lippiatt (2007)
	Flooring (high resistance)	10-20	Bernard *et al.* (2000)
	Wall covering	2-10	Bernard *et al.* (2000)
	Roofing sheets	10-20	Chanda & Roy (2007)
	Roofing sheets	15	Piper (2004)
Rock (natural)	Marble tiles	75	Lippiatt (2007)
	Flooring tiles (general)	40-100	Piper (2004)
	‘Terrazo’ flooring	35-50	Piper (2004)
	Mineral wool	>50	Lippiatt (2007)
	Slate roofing tiles	50	Piper (2004)

Table 3.3. Continued.

Material	Component/service	Forecast Service life (years)	Reference sources
Steel (galvanized)	Roofing	35	Piper (2004)
	Pipes	35-50	Piper (2004)
	Roof claddings	35-45	Marteinsson (2003)
	Wall claddings	>60	Marteinsson (2003)
Steel sections (Galvanized)	Exterior wall framing	75	Lippiatt (2007)
	Walls and floors with no risk of water ingress or condensation	>200	Popo-Ola *et al.* (2000)
	Roof structures (insulated) with low risk of condensation	100	Popo-Ola *et al.* (2000)
	Roof structures (insulated) with some risk of condensation	60	Popo-Ola *et al.* (2000)
	Exterior doors	30	Piper (2004)
Wood	Columns and beams	60-150	Craven *et al.* (1994)
	Wood frame	60-150	Craven *et al.* (1994)
	Wood frame	75	Lippiatt (2007)
	Windows (Nordic pine)	35-40	Marteinsson (2003)
	Exterior doors	30-40	Piper (2004)
	Platforms and posts	20-35	Liska (1998)
	Solid wood flooring	30	Craven *et al.* (1994)
	Linoleum (mostly wood flower)	30	Lippiatt (2007)
	Linoleum (mostly wood flower)	20-35	Piper. (2004)
	Siding panels	40	Lippiatt (2007)
	Wood plank (interior wall)	20-50	Piper (2004)
	Wood plank (interior)	20-50	Piper (2004)
	Plywood (interior panelling)	15	Craven *et al.* (1994)
	Plywood (interior panelling)	15-20	Piper (2004)
	Plywood (sheeting)	85	Craven *et al.* (1994)
	Oriented Strand board (sheeting)	85	Lippiatt (2007)

Table 3.3. Continued.

Material	Component/service	Forecast Service life (years)	Reference sources
	Square posts in ground contact (treated softwood)	50 - 80	MacKenzie *et al.* (2007)
	Square posts in ground contact (untreated hardwood)	30 - 50	MacKenzie *et al.* (2007)
	Aboveground exposed deck (untreated heartwood)	60-80	MacKenzie *et al.* (2007)
	Aboveground exposed deck (treated sapwood)	>100	MacKenzie *et al.* (2007)
	External structural elements (treated sapwood)	90 - >100	MacKenzie *et al.* (2007)
	External structural elements (untreated heartwood)	45 - 80	MacKenzie *et al.* (2007)
	Poles (external use with treatment)	>35	USDA (1999)
	Poles (external use without treatment)	<20	USDA (1999)
	Ties (external use without treatment under light traffic)	10-15	USDA (1999)
	Ties (external use without treatment under heavy traffic)	2-3	USDA (1999)
	Ties (external use with treatment under heavy traffic)	25-40	USDA (1999)
Wood coatings	Organic solvents preservatives (external finishes)	2 - 3	MacKenzie *et al.* (2007)
	Paint (external finishes)	7	Williams & Feist (1993)
	Paint (external finishes)	7 - 10	MacKenzie *et al.* (2007)
	Paint (windows external finishes)	3-5	Cruz *et al.* (1997)
	Paint (external plywood)	<10	Cruz *et al.* (1997)
	Varnish (windows external finishes)	<3	Cruz *et al.* (1997)
	Varnish (external finishes)	<3	Cruz *et al.* (1997)
	Windows (coatings)	2-4	Craven *et al.* (1994)
Wool	Carpet	25	Lippiatt (2007)

3.2 *Recovery scenarios for selected building materials and components*

A survey of the recovery potential for selected building materials and components is presented here. Main types of construction & demolition waste (C&DW) are covered: mixed C&DW, concrete, blocks, bricks and tiles, stone, gypsum, glass, thermal and moisture protection materials, asphalt, timber and engineered wood, plastics, steel and stainless steel, and non ferrous metals.

Recovery scenarios such as reuse, recycling, and incineration, their environmental, technical and economic feasibility, and recovery methods are also addressed. However, incorporation of wastes and by-products from other industries in building materials production is not reviewed.

The survey shows clearly the complexity of recovering building materials mainly due to the type of connections normally employed, and to the use of composite materials, such as concrete and mortars, and engineered wood. Thus, operations of separation, sorting and cleaning of building material wastes are needed for their reprocessing. Several composites are not suitable or too costly to decompose, making their reprocessing unfeasible.

Opportunities for reuse are feasible for a large number of materials employed in structural frames, masonry, and finishing. Changes from closed connections to open connections would increase the amount of reusable materials.

3.2.1 *Mixed C&DW*

Construction debris refers to bulk arising from demolition works composed of mixed non reclaimed inert materials such as earthen soil, concrete, stone, block and bricks, tiles, lumber, glass, and stoneware. Recycling of these kinds of materials involves a primary processing of sorting, crushing, dry separation (e.g. gravity separation, electromagnetic separation and microwaves), wet separation (e.g. sink-float methods, flotation methods) (van Dijk *et al.*, 2000), the level of which depends on the composition and contamination degree of the initial debris and the application for which it will be used (Coventry *et al.*, 1999, Huang *et al.*, 2002).

Mixed stony rubble consisting of concrete and masonry must be separated and broken in such a way that uncontaminated aggregates are obtained. The coarse fraction may be used as coarse aggregates in concrete products, the fine fraction may be used as a sand substitute in concrete, and the small sludge fraction must be disposed of (Mulder *et al.*, 2002).

Mixed construction and demolition waste (C&DW) processing has additional process steps in order to separate gypsum and hazardous materials by using advanced detection and separation techniques. Experiences to remove contaminating covers from concrete and masonry surfaces, such as plaster and tiles, using microwaves were carried out with promising results (Gerlach *et al.*, 2002). Currently, hazardous wastes have to be disposed of, but gypsum can be recycled. Remaining material is separated into a mineral fraction to be treated as mixed stony rubble, and a combustible fraction to be used as fuel (Mulder *et al.*, 2002).

Recycling of these different kinds of construction waste as substitutes for traditional composition of concrete has been extensively studied with successful and promising results. Concrete, bricks, glass and ceramics are pointed as substitutes for aggregates and sand coarse in concrete mixes production. Low prices of river sand and natural aggregates are still an obstacle for a wider use of recycled aggregates. Costs comparison shows slight differences, but net eco benefit of recycling is significantly greater, being this difference the added value of recycling activities (Hendriks *et al.*, 2002).

Suárez (2003) stresses the fact that aggregates from C&DW are suitable for non-structural purposes such as stucco mixes, masonry mortars, concrete blocks, and low strength concrete, remarking that cost savings is about 35%, when compared to natural aggregates.

Batayneh *et al.* (2007) incorporated demolished concrete as a replacement up to 20% of coarse aggregates, and plastics and glass as replacements up to 20% of fine aggregates in concrete mixes. Mechanical and workability disadvantages were pointed, limiting the application of these kinds of concrete mixes, and cost advantages were emphasized regarding availability of primary materials. Sànchez de Juan & Alaejos Gutiérrez (2008) point out that only recycled concrete aggregates with mortar content less than 44% can be used for structural concrete production.

Concerning recycling of fine fractions of C&D waste and clay brick debris, coarse fraction may be used as aggregate for lightweight concrete, and sand fraction can be used as aggregate for mortar with no differences of properties (Mueller & Stark, 2002; Reinhold & Mueller, 2002; Bianchini *et al.*, 2005). Poon & Chan (2007) present similar results for replacing natural sand by crushed brick and tile aggregates up to 20%, leading to a decrease of compressive strength as the fine crushed brick or tile was increased.

To avoid loss of properties in concrete based on recycled bricks, polymer admixtures may be incorporated as additives. Such polymer modified concrete has approximately the same value of compressive and bending strength, better waterproofness, and frost resistance (Jankovic, 2002). However, due to worse modulus of elasticity and greater creep stains caused by polymer admixtures, have a restricted use in the production of solid and hollow bricks.

Masonry debris may also be used as a raw materials mixed with clay to produce new clay bricks, with no problems for the production process (van Dijk *et al.*, 2002).

Corinaldesi & Moriconi (2009) showed low mechanical strength for cementitious mortars prepared using different recycled aggregates, such as concrete scraps, bricks and demolition waste as substitutes for natural sand, in comparison with traditional mix. However, mortars incorporating recycled aggregates presented higher bond strength for brick masonry applications, which is more important than mechanical strength for such purpose.

Another application for aggregates produced from reclaimed building materials is in hot mix asphalt (Shen & Du, 2004). A replacement up to 100% of natural coarse aggregates by recycled aggregates (crushed concrete and bricks) evidenced less permanent deformation when compared with traditional mixes, due to an improvement in deformation resistance

Porcelain from sanitary stoneware was also tested as a partial substitute of the coarse aggregates portion in conventional concrete admixtures. Guerra *et al.* (2009) showed similar mechanical characteristics for concrete with recycled crushed porcelain when compared with conventional concrete, such as compressive strength.

3.2.2 *Concrete*

Concrete is a popular material and is present in buildings all over the world. Structural concrete is used as pre-fabricated elements and used cast-in-place. Structural concrete is a composite material made with cement, reinforcing steel, aggregates, sand, water, fillers, and additives. Thus recycling opportunities for concrete and structural concrete need a complex process for the separation of constituents (Hendriks *et al.*, 2000).

Reuse of concrete elements is limited to its disassemblability. Pre-fabricated elements may be reused in new buildings if still verifying standard requirements. Several dismountable precast concrete systems are available in the market. However precast joints must assure system's disassembly by using accessible mechanical joints such as bolts and screws (van Dijk *et al.*, 2000). A reuse of cast-in-place concrete elements is suggested after these elements having been cut, with a limited range of low-grade applications such as marine underground banks and poles (CICCP, 1997).

Recycling of crushed concrete waste as an aggregate began at the end of World War II (Wainwright *et al.*, 1994). Recycled concrete is commonly used for a few low-grade options, mainly as bulk fill or hardcore for roads and as an alternative to primary aggregates, replacing natural stone aggregates (Coventry & Guthrie, 1998; Coventry *et al.*, 1999; Hendriks *et al.*, 2000; Dumitru *et al.*, 2000; Marmash & Elliott, 2000; Kernan, 2002; Lauritzen, 2004; Petkovic *et al.*, 2004; Robinson Jr. *et al.*, 2004) and in precast concrete blocks with up to 75% recycled concrete aggregates (Collins, 2003).

However, recycled concrete properties and homogeneity must be taken into consideration and characterization of reclaimed concrete is rather important. If certain levels of impurity are acceptable for most unbound applications, “non clean” concrete incorporating reinforcement additives and contaminants from other building materials may influence properties of new fresh concrete (Coventry *et al.*, 1999). Requirements for concrete recycled aggregate regarding impurities prevent negative effects on strength and durability, such as slower setting of the cement, corrosion of reinforcing steel by chlorides presence, forming of ettringite due to gypsum presence, alkali-silica reactions due to Pyrex glass presence, and reduction of compressive strength (Hendriks *et al.*, 2000; Kasai, 2004).

Then, before being used in new materials, thermal and mechanic treatments (e.g. crushing, magnetic and eddy current separation, kilning, and vibrating separation) are applied to clean concrete rubble by disintegration of the concrete matrix to recover its constituents (i.e. gravel, sand, cement stone and reinforcing steel) (Larbi *et al.*, 2000; Mulder *et al.*, 2002). Linb & Mueller (2003) suggest electro-hydraulic crushing of concrete using shockwaves generated by an electrical discharge underwater, as an efficient process to obtain higher percentages of cement paste free of aggregates.

Clean crushed concrete is normally suitable as a substitute for stone aggregates for all types of concrete. However, several studies conclude that some limitations to natural aggregates replacement must be observed.

It is currently accepted that a replacement of not more than 20% of the volume of the coarse aggregate with crushed concrete will cause no problems to workability, compressive strength and deformation (Gottfredsen & Thogersen, 1994; Coventry *et al.*, 1999; Hendriks *et al.*, 2000; Sagoe-Crentsil *et al.*, 2001; Collins, 2003; Dhir & Paine, 2007). A 100% replacement would reduce compressive strength between 10 to 20% (Wainwright *et al.*, 1994; Coventry *et al.*, 1999) and a 10% greater thickness must be considered to ensure adequate fitness to prevent deformation. Kasai (2004) and Topçu & Sengel (2004) all suggest a possibility of 30% replacement of regular aggregates by recycled concrete aggregates and also state that there are significant reductions in strength and durability for 100% replacements.

Furthermore, Wainwright *et al.* (1994) and Merlet & Pimienta (1994) remarked that for natural sand replacement, fine recycled concrete aggregates may substitute 50% of sand volume with improvements in strength, porosity and permeability.

Natural aggregates replacement by recycled concrete aggregates increases concrete porosity (Gómez-Soberón, 2002). Absorption for recycled aggregates is higher than for natural aggregates, with typical values of 5 to 6%. Also drying shrinkage will be higher than normal due to the increased amount of hardened cement paste (Collins, 2003). However, it is suggested that higher values for porosity than that of natural aggregates can be an advantage for sound absorption products such as sound barriers for freeways (Krezel & McManus, 2000).

As main environmental and economic advantages, recycling of concrete reduces natural aggregates depletion, conserves energy, lowers construction costs, reduces landfilling, and seems to be an efficient destination for concrete waste. Recycled concrete aggregates reduce the amount of CO_2 emitted from around 6,900 to 7,700 g per ton for gravel and sand extraction to approximately 3,000 g per ton (Estévez *et al.*, 2003).

However, Colins (2003) remarked that due to concrete waste contamination and relatively low usage of recycle concrete aggregates, there is not sufficient concrete waste to supply near 20% of the demand for aggregates at this level, making higher percentages for recycled aggregates incorporation unnecessary.

3.2.3 *Clay blocks, bricks and tiles*

Blocks, bricks and tiles are commonly reclaimed for reuse and recycling purposes. Reuse of bricks and blocks involves manual work to be taken apart at a rate of 2000 bricks per person per day (Coventry *et al.*, 1999). Masonry mortars used for joining influences recovery efficiency: bricks joined with lime based mortars are easier to remove than those joined with cement-based mortars. Usually, bricks and blocks are damaged and covered in mortar (Hurley *et al.*, 2002) and additional works of sorting and cleaning are also required in reclaimed processes. Due to labour-intensive processes, reuse of bricks is usually reduced to outdoor bricks (Hendriks *et al.*, 2000) (see Figure 3.2). Due to high costs for bricks separation and presence of contaminants, it is not always possible and economically viable to reclaim bricks and blocks.

Figure 3.2. Rinker School of Building Construction, University of Florida: bricks from demolished building were reused in the new building.

Thermal treatments are employed to clean bricks rubble in order to remove contaminants and to separate mortar from bricks. Kristensen (1994) describes the process of reburning in three steps: decomposition of hardened cement at app. 500°C, resolution of hardened lime at app. 900°C, and hard burning of clay bricks between 1000 to 1060°C. The outputs of this thermal process are whole hard burned bricks, quicklime and sand, and bricks waste to be used as aggregates in concrete. Mortar and pieces of bricks may also be used for the production of new bricks (Mulder *et al.*, 2002).

Salvaged blocks and bricks must be tested and suitable for the proposed application. These tests may include absorption and freeze thaw cycle tests (Kernan, 2002). Generally, most bricks and blocks reclaimed during dismantling of buildings will not be able to meet mechanical and chemical requirements (Hobbs & Hurley, 2001). Particular care should be taken over bricks with high sulphate content and gypsum plaster due to failures caused by sulphate attack (Coventry & Guthrie, 1998).

For old clay tiles, there are some chemical and mechanical constraints upon reuse such as colour variation, rough surface, recrystallisation of salts, and cracking (Coventry *et al.*, 1999).

Usually, due to high recovery costs and quality aspects, blocks, bricks and tiles are treated as generic construction debris and recycled as hardcore in road pavements and aggregates in concrete and clay products. Crushed masonry waste may replace 10% of gravel content in concrete with no change in mechanical properties (Hendriks *et al.*, 2000). Bricks waste may also be recycled as a substitute of sand for concrete (Hansel, 1994; Azzouz *et al.*, 2002, Mueller & Stark, 2002).

Hansel (1994) refers the possibility of total reutilization of crushed masonry as raw material for new bricks production, by reactivating limes based binders trough old masonry burning in order to produce new bricks in a calcium silicate process. These bricks showed to be satisfying for most types of masonry including for structural masonry, less sensitive to changes in moisture content than normal bricks, and may be more resistant to acid rain than those made with sand aggregates.

3.2.4 *Stone*

Natural stone blocks have been reclaimed trough whole construction and building history. Architectural stone from past ages and civilizations was often reclaimed by new builders and became part of new construction and buildings.

Stone blocks may come from old masonry, pavements, and architectural ornaments and they are suitable for ready reuse. However, sorting, cleaning, and resizing operations may be needed. Some constraints for stone reclaim may be due to environmental contamination (e.g. urban air pollution) and crystallization of salts.

Recycling of stone includes crushing processes for hardcore and aggregates production.

3.2.5 *Gypsum*

Gypsum consumption has increased on recent decades due to its application in gypsum blocks for load bearing and non-load-bearing interior walls, in plasterboard plates for walls and ceilings, in plasters, and as a cement additive.

Gypsum, both natural and synthetic, may be present in construction waste both as a contaminated product due to finishing products and paints, and as a contaminant itself. Gypsum presence in recycled aggregates affects hardening reactions during concrete production, due to its high solubility, low hardness and low density (Hendriks *et al.*, 2000; Vrancken & Lathem, 2000). Furthermore, disposal of C&DW with high gypsum content is a source of aquifers contamination due to its leachability that imposes environmental limitations to its disposal. Under certain conditions, gypsum reacts to produce hydrogen sulphide gas (H_2S), a highly toxic and flammable gas, and sulphide leachates (WRAP, 2006). Musson *et al.* (2008) proposed a method to measure gypsum content of C&DW by measuring sulphate leached in an aqueous solution, in order to prevent environmental contamination.

The European Directive 1999/31/EC on Landfill of Waste (EU, 1999) reclassified high sulphate wastes including plasterboard as non-hazardous non-inert wastes The Directive requires all gypsum to be landfilled in a separately engineered cell, separated from other waste type, in non-hazardous landfill sites. Similar legislation has also been adopted in North America. Due to these regulations, limitations for gypsum landfill were imposed, its disposal thus becoming too expensive, increasing opportunities for the recycling of gypsum products

Gypsum is the hydrated form of calcium sulphate and can be recycled infinitely by means of calcination and rehydration cycles (Vrancken & Lathem, 2000). However, due to high levels of purity required for certain gypsum products, means of collection and separation of gypsum can be very expensive and difficult to perform and recovered gypsum quantities may not be enough for recycling processes to become economically feasible. Being plasterboard the main source of clean reclaimed gypsum, several studies focused on plasterboard reclaim techniques and collection processes (see Figure 3.3), in order to maximize quantities and uncontaminated waste (Lee, 2006; WRAP, 2006, 2006a; Storton & Meaden, 2007).

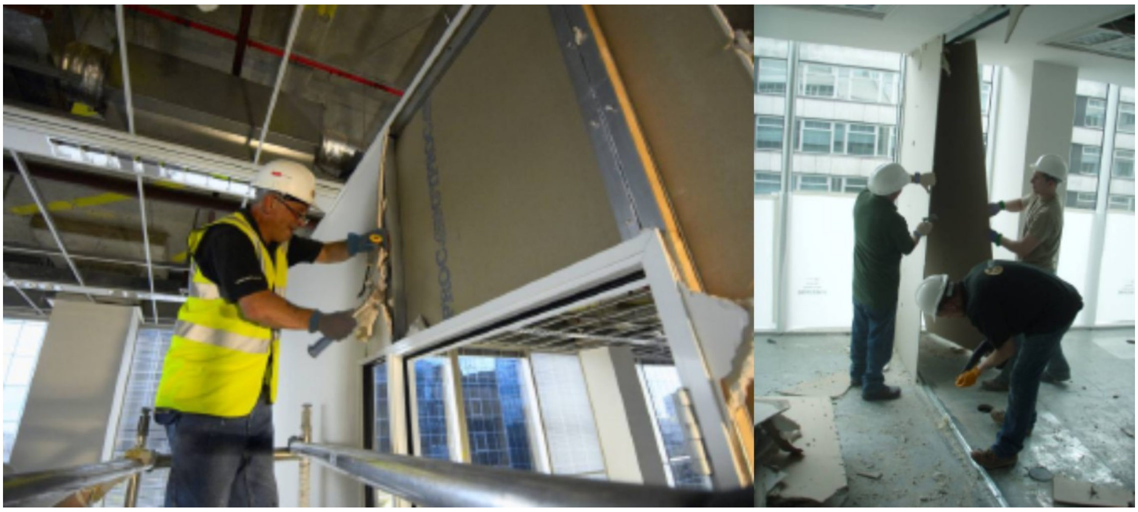


Figure 3.3. Recovery of plasterboard (Lee, 2006).

(1) Recycling of plasterboard for new plasterboard manufacture

Plasterboard is the major source for reclaimed gypsum in building construction. Being a composite material made of paper and gypsum, recycling processes are more complex in order to separate its constituents.

Rathmann (1998) stated that separating the paper cover from the gypsum core makes recycling more expensive than using virgin gypsum. Instead he suggests combining gypsum with cellulosic wood wastes to produce a durable, fire-resistant, and paper less plasterboard, and also to produce lightweight non-structural partition blocks.

However, Kernan (2001) argues that in North America most plasterboard panels are available in market with up to 20% post-industrial and post-consumer recycling gypsum.

WRAP (2006, 2006a) also pointed out that in average 20 to 25% of recycled gypsum can be integrated into the manufacture of new plasterboard, and up to 40% recycled gypsum content does not affect properties of the final product. Townsend & Cochran (2003) refers that plasterboard manufacturers typically recycle post-manufacturer scrap at their facilities, representing as much as 10% to 20% of gypsum feedstock.

Recycling of post-consumer plasterboard is an alternative to landfill and involves the following steps (Marvin, 2000; WRAP, 2006, 2006a; Allcorn & Welch, 2007) (see Figure 3.4 and Figure 3.5):

(i) Segregation and collection, that takes place on-site to ensure a low cost separation system and collection;

(ii) Haulage and storage in a warehouse located close to a plasterboard manufacturing plant to reduce transportation costs;

(iii) Cleaning and separation of gypsum from the paper, including screening, handpicking, and magnetic removal of nails and screws;

(iv) Separation of paper liner from the gypsum core, and paper shredding or pulping before being sent to paper recycling;

(v) Shredding and granulating of gypsum core into powder;

(vi) Reprocessing recycled gypsum in combination with raw gypsum to form new plasterboard.

Figure 3.4. Recycling of plasterboard at Gypsum Recycling: collection, haulage, storage, and granulating (mobile unit) (WRAP, 2006a).

Figure 3.5. Plaster paper by-product, and final recycled gypsum product (WRAP, 2006).

Also mechanical methods for easy recovery of gypsum components for reuse should be developed. Thormark (1998) pointed the possibility of 45% reuse of the reclaimed plasterboard plates by direct sawing of panels from the walls.

(2) Recycling gypsum in cementitious products

Application of recycled gypsum in cementitious products manufacture has some constraints, such as potential constituents that affect purity of recycled gypsum (e.g. additives and paper content), particle size and dehydration (Allcorn & Welch, 2007).

However, due to high $C0_2$ emissions from production of conventional cements, there is an increasing interest in alternative cement binders with high gypsum content, because they produce lower $C0_2$ emissions during manufacture. Those alternatives are calcium sulfoaluminate (CSA)-belite cements and supersulfated cements that use both gypsum in their formulations. Because ettringite is one of the main cementing phases in CSA cements, the addition of further sulphate becomes acceptable thus creating new applications for recycled gypsum.

Cement mixes of CSA and recycled gypsum from plasterboard waste were tested for production of concrete block paving and aggregate concrete block applications. The products developed have significant compressive strength and economic benefits because the material is cheaper than cements and natural gypsum (Dunster, 2008). Testing showed that block pavers may incorporate up to 33% of recycled gypsum in concrete mixtures.

Recycled gypsum from plasterboard waste may substitute raw gypsum as a control agent for set time in ready mix cements production. Townsend & Cochran (2003) and Clamp (2008) remarked that gypsum paper content must be kept bellow 1% for such application.

Development of recycled gypsum-clay mixes for clay blocks and bricks is another application for plasterboard waste (Biggs, 2007). The gypsum-clay blocks were air or force dried, thus reducing CO_2 emissions and energy embodiment. Blocks produced with these mixes enhanced physical properties if compared with natural clay.

Another application for recycled gypsum is in road foundation construction as a constituent of cementitious binders, used for clayed soils stabilization and roller-compacted concrete production (Ganjian *et al.*, 2007).

(3) Other applications for recycled gypsum

Reclaimed gypsum may also be recycled for several other applications (Marvin, 2000; Vrancken & Lathem, 2000; Townsend & Cochran, 2003; Cartwright, 2007; Musson *et al.*, 2008):

(i) In production of gypsum anhydrite;

(ii) In production of sulphuric acid;

(iii) In soil amendment: for increscent levels of sulphur and calcium nutrients for plants, for improvement of soil structure due to its absorption properties, for drainage improvement, for reclamation of sodium rich soils, for reduction of phosphorous leaching, and improvement of acid sub soils;

(iv) And in composting systems amendment by binding odours associated with ammonia.

Recycled gypsum also may be used for slope stabilization of sandy loam and clay soils. Applications at between 4 kg/m^2 of recycled gypsum on slopes showed to be effective on reduction of soil erosion and slippage when compared with untreated soils (Lawson, 2007).

3.2.6 *Glass*

Glass is used in building construction mainly as flat glass for windows. Recovered glass is suitable for both reuse and recycling.

Some potential problems with glass collection from C&DW are related to heterogeneity of collected glass (i.e. different chemical makeup); mixed of clear and tinted glass, contaminants such as metal attachments, adhesives, glass printing, plastic, or waste particles from concrete, mortars, bricks, stones, and porcelain (EAFGM, 2005). Contamination of flat glass leads to a loss of production due to a loss in quality, and thus contaminated glass may not be able to be recycled. In melting processes, inert contaminants may not melt in the furnace giving rise to “stone” defects, metals can react giving rise to gas bubbles, and glass ceramic materials and heat resistant borosilicate glasses (e.g. “Pyrex”) will cause defects in the finished products and can stop the liquid glass flow in the glass molding machinery (Enviros, 2003).

If reclaimed glass is taken with care during building dismantling, it would be possible to reuse it as glass panes, due to their high durability and to the fact of being chemically inert. The properties of reused windows could be similar to new products (Coventry *et al.*, 1999).

For recycling processes, double glazed units must be cleaned of space bars, silicone gel, and sealant to get two separated whole panels of glass.

Due to the high purity requirements in flat glass manufacturing, it is not possible to recycle reclaimed glass for new flat glass manufacturing. For float glass production, a type of flat glass, chemical composition is extremely critical and the cullet composition must exactly match the glass composition in the furnace. Thus, manufacturers of flat float glass only recycle material that originates from their own downstream processing plants (Enviros, 2003, 2004).

However, there are a set of other recycling options. Glass may be recycled as glass fibres in the manufacture of glass fibres, in the replacement of virgin glass materials for foamed glass insulation, as a strengthener of cement, gypsum or resin products, and as aggregates for road construction, concrete and flooring products.

(1) Recycling glass for aggregates production

The aggregates obtained from glass recycling have several applications, such in loose fill, asphalt, concrete, pipe bending, and backfill, replacing crushed rock, gravel, and sand.

Conventionally glass is not suitable for use in concrete due to alkali-silica reactions (ASR). However, several ways are pointed to avoid ASR and its damaging effects: grinding glass to fine ground, incorporating mineral admixtures such as metakaolin or fly ash to reduce expansions, glass coating with zirconium, changing glass chemistry, using low-alkali cements, sealing concrete to keep it dry, and developing ASR-resistant cements (Meyer & Shimanovich, 2004).

Using waste glass as a substitute of coarse aggregates in concrete seems to have additional limitations. Topçu & Canbaz (2004) state that recycled glass aggregates do not have a remarkable effect on the workability properties. Regarding compressive and flexural strengths, they decrease in proportion to an increase in recycled glass aggregates, being preferable to use waste glass as fine aggregates replacement.

However, recycled glass aggregates have some advantages regarding normal aggregates: zero water absorption, excellent hardness superior to most natural aggregates, improvement of flow properties of fresh concrete, and very finely ground glass has pozzolanic properties serving both as partial cement replacement and filler (Enviros, 2003, 2004; Meyer & Shimanovich, 2004).

Sobolev *et al.* (2007) presented the so called ECO-cement where large amounts up to 70% of Portland cement clinker can be replaced with waste glass. ECO-cement with 50% of waste glass has properties similar to normal Portland cement regarding compressive and flexural strength, improved by reducing water demand.

Glass aggregates may also be used in paving stone, concrete masonry blocks, and decorative architectural elements such as building façade elements, precast wall panels, and floor and wall tiles (Meyer & Shimanovich, 2004).

Other alternatives for recycled glass application as aggregates are currently being studied. Lee *et al.* (2008) proposes the production of artificial stone incorporating 40% of waste glass powder and 60% of fine granite aggregates bonded with unsaturated polymer resins, registering higher performances in terms of strength and water absorption when compared with natural stone slabs.

(2) Other applications for recycled glass

Several alternative applications are possible for recycled glass (Enviros, 2003, 2004):

- (i) As filtration media of drinking water, wastewater, swimming pools, and fisheries, by replacing sand, anthracite, and garnet;
- (ii) As abrasive, by replacing silica sand, copper slag, and anthracite;
- (iii) As binder in bricks, ceramics, and pottery, replacing clay and mineral fluxes;
- (iv) In foamed glass insulation for construction applications, by replacing virgin glass materials;
- (v) As filler in paint and plastics, by replacing titanium dioxide and calcium carbonate.

Addition of glass in brick –making clay reduces firing temperature during the brick-making process. Another effect is that glass improves frost-resistance of clay bricks. A replacement of more than 10% of clay by finely grounded glass improves compressive strength and reduces water absorption of clay bricks.

3.2.7 *Thermal and moisture protection materials*

Fibreglass and rock wool (mineral wool) are used mainly for thermal and acoustic insulation. These panels are easily reused because they are held in place by ballasts and normally are not damaged by fasteners (Kernan, 2002).

According to the European Directive 1999/31/EC (EU, 1999), rock wool panels cannot be disposed without pre-treatment which may be made by physical, chemical or thermal processes. Physical treatment includes segregation and volume reduction of rock wool panels. As an alternative to disposal, rock wool may be reused or recycled.

Rock wool panels may be reused, or can be used as a raw material for new Rockwool products or even used as an aggregate material (Hendriks *et al.*, 2000).

For recycling purposes, mineral wool panels and steel faced composite panels must be shredded. At the same time, the shredder separates the steel from the mineral wool via a magnetic belt (BRE, 2008) (see Figure 3.6). Recovered mineral wool has sufficient quality to re-enter into the manufacturing process of new planes.

Polystyrene panels are suitable for reuse if recovered intact; otherwise it will follow the recycling processes established for other plastics.

For roofing and waterproofing membranes, such as PVC or asphalt membranes, there is not a feasible potential for reuse or recycling, due to their short service lives. In addition, installation procedures makes removable difficult or just impossible (Kernan, 2002). Usually these materials contaminate the surface of the materials in which they are bonded, such as concrete and mortars.

Figure 3.6. Composite panel recycling machine and separation of mineral wool from steel fraction (BRE, 2008).

3.2.8 *Asphalt*

Reclaimed Asphalt Pavements (RAP) are intended for recycling, combined with a required amount of virgin asphalt binder and new aggregates for the application in new pavements, with no significant difference between mechanical behaviour of recycled and virgin mix (Aravind & Das, 2007). Authors also locate cost savings between 12% and 54% for different granular layer thicknesses. Chiu (2008) pointed also the environmental benefits of replacement of traditional hot-mixed asphalt with recycled hot-mixed asphalt by reducing the eco-burden by 23% for both a 6 and 40 years life span.

Asphalt for pavements may also incorporate other recycled materials in its mixture, reducing the amount of quarried aggregates. Waste glass, steel slag, tires and plastics (LPDE) were tested as substitutes for pat of the aggregates fraction in asphalt mixtures for pavements (Huang *et al.*, 2007) with reasonable results.

3.2.9 *Timber and engineered wood*

Although being a natural resource, availability of naturally durable hardwood species has declined. Due to this exhaustion process and regulations for protection of tree species, wood industry turned to softwoods from managed forests or plantations (Hill, 2006).

Thus, to meet both market demands and environmental and durability requirements, wood is present in buildings in several ways: as natural wood (hardwood and softwood), modified wood (treated softwood to improve durability and strength), and engineered wood (wood composites). All the three types of products are employed for structural and finishing purposes.

The range of wood composites for building construction is wide and includes glued-laminated (glulam), plywood, particleboard, flakeboard, waferboard (WB) and oriented strandboard (OSB), and fibreboard (low-density fibreboard and medium density fibreboard (MDF)) (Berglund & Rowell, 2005).

For wood-based resources, the breakdown of the raw materials follows several steps from logs to lumber, to veneer, to chips, to fibres, to charcoal, and finally to fuel. Similarly, the salvage ability of wood is usually possible also through a set of cascade chains that extends their life cycle by reusing components, reprocessing into particleboard, pulping to form paper, and incineration for energy recovery (Nordby *et al.*, 2007). This principle is valid both for timber and engineered wood. However, adequate options for wood reclaim depends on the form in which timber and engineered wood is recovered, i.e. whole timber elements or timber fragments, and depends on the level of contaminants such as preservatives, paints, glues, and resins (Coventry & Guthrie, 1998).

Timber elements such as beams and columns can be directly reused, ideally for the same purpose, but the amount of damage is a constraint on the reclaimed elements (Kibert & Languell, 2000; Hurley *et al.*, 2002). Chini & Acquaye (2001) noticed that for six case studies, 57% of salvaged lumber had damages. However, when compared with virgin lumber, salvaged lumber was on average 50% denser with recommendable reuse for structural purposes.

Reuse of timber elements may include previous operations of cleaning, de-nailing, grading, sizing, and strength tests if reused for load-bearing applications (Coventry *et al.*, 1999). The recycling of these elements has also a wide range of applications in wood composites production, flooring, and doors.

Reuse of engineered wood elements such as glued-laminated (glulam) structural components needs additional texts to the adhesive bond and straightness. If not suitable for reuse, glulam elements may be cut horizontally between the lamination lines and the boards recycled for flooring boards manufacture (Kernan, 2002).

Recycling of wood depends on the form in which wood may be recovered and transformed as a raw material. Raw materials for wood composites are divided in veneer based composites (plywood), particle based composites (waferboard, oriented strandboard, particleboard) and fibres based composites (fibreboard, insulation board) (USDA, 1999). As so, recycling of wood as chippings is oriented for particle and fibre based composites production.

Applications for wood chips recycling include also wood-nonwood composites such as plastic lumber and wood-fibre cement composites.

Particleboard production is a result of the need and the opportunity to recycle large amounts of sawdust and sawmill chips at sawmills, bonding those fibre using synthetic adhesives (Arima, 2001; Berglund & Rowell, 2005). Due to their similar physical properties, recovery of wooden particleboards from buildings for production of new particleboards was studied as well as reusing board production residues. Lykidis & Grigoriou (2008), applying hydrothermal treatments for wood particles treatment and recovery, emphasized the limitations of wood particleboard recycling due to the decrease of mechanical properties when compared with non-recycled boards. Mixed compositions of recovered and fresh wood particles may be an alternative.

Wood chippings as a waste product can also be incorporated in lightweight mortars. Coatanlem *et al.* (2006) shows the feasibility of producing wood chipping lightweight concrete, by improving the bond between the wood waste and cement paste by mixing the wood chips in a sodium silicate solution before the concrete mixing. Disadvantages of using this material in humid environments due to wood deterioration were pointed. Wood sawdust may also be used as a supplement compound in lightweight cement composites for the production of bricks complying with relevant standards (Turgut, 2007).

Wood chips of different size and shape were also successfully tested for several purposes: animal bedding, bridleways, mulches, playground impact surfaces, pathways, and landscaping (ESYS, 2006, 2007; FPRC, 2007).

The consideration of incineration and landfill of wood waste face also some environmental barriers. Although being a natural resource, wood is in general modified in order to increase its durability and mechanical properties, or to produce engineered wooden products.

Landfilling options of wooden products may release $C0_2$ and CH_4 (greenhouse gases) to air, pollute subsoil water due to toxic compounds and build up hazardous substances in soil. The use of wood waste as an energy source has a lower heat efficiency when compared with oil and gas fuels, becoming another source of pollutants. Incineration of wood emits CO_2, CH_4, SO_2, NOx, HCl and dioxins to air, and heavy particles produced (e.g. ashes) may fallout in water and soil. Heavy metals, such as copper, cadmium, chromium, arsenic, lead, and mercury may be present in mixed wood waste (Irle *et al.*, 2004). Total recovery of metals derived from preservatives is not achievable and dissipation of metals to the biosphere is inevitable. Alternative strategies for metals removing prior to incineration have been proposed (Hill, 2006).

Several methods for contaminants detection in wood waste were developed: the “Pan Colour Indicator Technique” that uses PAN (1-(2-pyridylazo)-2-naphthol) mixed with organic solvents (e.g. methanol, and n-propanol) and distilled water, to detect copper contamination such as copper-chrome-arsenate, copper-chrome-boron, copper-chrome-phosphate, and copper organics (Irle *et al.*, 2004; Sawyer & Irle, 2005, 2005a, 2005b; FPRC, 2007a). Non chemical techniques are also available such as devices for measuring metal concentrations by measuring x.rays that fluoresce from the specimen (Irle *et al.*, 2004).

As an alternative to incineration, Arima (2001) pointed the production of charcoal by heat treatments of wood waste, in order to reduce pollution from wood burning. The charcoal produced can be used for soil improvement for plants growing, absorption of odours, moisture and for preservatives.

Composting of chipboard and MDF with organic waste from garden and kitchens are also a method for nitrogen capture to be used in soil amendment to provide plant growth benefits (ADAS, 2007, 2007a). Although bonding agents may be reduced by the composting process, they are unlikely to degrade completely. Thus, some limitations regarding hazardous constituents and plastic and paint coatings are a barrier to this purpose. Only phenol resins are suitably degradable, while melamine and isocyanates are resistant to biodegradation. These barriers impose testing procedures to final products.

3.2.10 *Plastics*

Due to their key properties (e.g. mechanical, thermal, weathering, permeability), polymers have a wide range of applications in building and construction as bulk, foam, fibre reinforcement, adhesive, and sealant materials (Halliwell, 2002).

Basically, plastics may be grouped in two major kinds: thermoset and thermoplastic polymers. Both thermoset polymers (Epoxy, Phenolic, Acrylic, Silicone, Polyester, Melamine-formaldehyde resin) and thermoplastic polymers (Polystyrene (PS), Polyvinyl chloride (PVC), Polyamide (PA), Polypropylene (PP), Polyethylene (PE), Polyethylene Terephthalate (PET), Polymethylmethacrylate (PMMA), Polycarbonate (PC)) have a wide application in building materials manufacture.

Polyurethanes (PUR), the most versatile group of polymers, may range from soft thermoplastic elastomers to hard thermoset rigid forms (Chanda & Roy, 2007). Rigid polyurethane foams are often used in building construction for insulation and flooring, due to their strength, toughness, high void volume, and low pressure drop (Thomson, 2005; Lee *et al.*, 2007).

Polymers are processed into a desirable size and shape by means of heating for polymers to flow, and cooling to preserve the shape, such as extrusion, injection moulding, thermoforming, blow moulding, and rotational moulding (Baker & Mead, 2002).

Due to its low cost and good resistance and weathering behaviour, Polyvinyl chloride (PVC) has become the most used plastic in buildings and has applications in rigid profiles and sheets for window and door frames, flexible sheets and foils for flooring and roof waterproofing, and water and gas pipes (Brydson, 1999; Baitz *et al.*, 2004). Other plastics such as polyethylene, polypropylene, and polystyrene are also commonly used for insulation and pipes production.

Thermoset polymers are generally used as curing agents (hardeners), coatings, adhesives, sealants, and solvents, for several applications in concrete, mortars, repairing, waterproofing, and insulation (Irfan, 1998; Wright, 2004).

Due to the environmental burden of plastics lifecycle, their recovery becomes an important issue to be taken into account. Opportunities for plastics reclaim cover both incineration for energy recovery and recycling processes, both mechanical and chemical (Azapagic *et al.*, 2003; O'Neill, 2003). Plastics recycling processes are classified in primary recycling (i.e. applications producing the same or similar products), secondary recycling (i.e. products with less demanding specifications), tertiary recycling (i.e. recycled plastic as chemical raw material), and, although not being a true recycling process, quaternary recycling (energy recovery) (Goodship, 2001, Lundquist *et al.*, 2001, Mazumdar, 2002; Selke, 2004; Chanda & Roy, 2007) (see Table 3.4).

Table 3.4. Standard names of processes for plastics recycling and their purposes.

Term	Type of recycling	Purpose
Primary recycling	Mechanical recycling	Same or similar products
Secondary recycling	Mechanical recycling	Down cycling (low quality applications)
Tertiary recycling	Chemical recycling	Feedstock (monomers, oil fuels, gases, HCl)
Quaternary recycling	Incineration	Energy recovery

(1) Plastics incineration

Incineration and thermal processes are classified as quaternary recycling and are applied for volume reduction by about 90 to 95 %, and heat content recovery (Scott, 1999; Goodship, 2001, Tukker, 2002; Siddique, 2008). Incineration is often considered the only suitable method for recovery of plastics for which there is no market, such as plastic composites scrap (Zia *et al.*, 2007).

Incineration is generally comprised by the following steps: combustion, heat recovery, and gas and liquid-effluent treatment (Baitz *et al.*, 2004).

Energy recovery from plastic wastes becomes a good source of heat, because their resinous compounds have a heating value almost equivalent to that of coal (Siddique, 2008; Siddique *et al.*, 2008). For example, due to high energy demands of fuel, cement kilns use pre-treated waste streams as fuels including solid plastic wastes (Lundquist *et al.*, 2001).

Incineration processes may produce different outputs, such as steam (energy), inert slag, and high quality HCl from plastics with high chlorine content such as PVC (Tukker, 2002; Baitz *et al.*, 2004). These by-products from incineration may be used in other manufacturing processes.

(2) Plastics recycling

Once plastic waste occurs in the form of products, plastic waste recycling can be difficult to achieve, depending on how plastics are more or less mixed or present as part of composite materials. For example, in the year 2000, the European Union only recycled 3% of PVC post-consumer available waste and incinerated 15% (Baitz *et al.*, 2004).

Due to their intrinsic properties, thermoset and thermoplastics cannot be reprocessed in the same manner, *i.e.* thermoset polymers do not re-melt. As a consequence, plastics must be sorted for recycling purposes, and also because plastics are not compatible with each other, thus occurring a separation process phase if two non-mixing polymers are put together (Goodship, 2001; Azapagic *et al.*, 2003).

Thermoplastic polymers can be heated and softened and easily recycled a number of times without significant changes to their structure. However, recycling aged thermoplastic materials needs the addition of 60 to 70% of virgin polymer to obtain mechanical properties of comparable quality (Coventry *et al.*, 1999). Thermoset polymers cannot be processed repeatedly and their recycling is carried out chemically or by grinding into a powder.

Recycling of plastics involves mechanical recycling processes (i.e. size reduction, washing, sorting, agglomeration, extrusion and regranulation) and chemical recycling processes (i.e. breaking down polymers into their constituent monomers and feedstock production) using chemical modification or thermal reprocessing in order to produce new raw materials for petrochemical processes and polymers production (Goodship, 2001; Cornell, 2003; Harper & Petrie, 2003; Baitz *et al.*, 2004; Pickering, 2006; Buekens, 2006).

Recycled plastics are currently used in several construction applications, such as fillers, window frames, pipes, insulation foam, cladding and decoration panels, and wood-plastic composites for street furniture, flooring, and plastic pilling.

(a) Mechanical recycling

Mechanical recycling is the most common method for plastics recycling, especially for thermoplastic polymers. Mechanical recycling is done by regrinding the polymer into powders allowing them to be reused as raw materials in the production of new plastic products (Goodship, 2001; Harper & Petrie, 2003; Awaja & Pavel, 2005; Zia et al., 2007).

Being both a thermoplastic and a thermoset polymer, Polyurethanes are suitable for every method of recycling. Mechanical recycling processes are currently applied to polyurethane rigid foams (Zia *et al.*, 2007).

Mechanical recycling processes are more economically more viable if applied to selected plastic flows: high volumes, recognisable products, and non composite plastics (Goodship, 2001; Tukker, 2002). Mechanical recycling will be more effective if produced recyclates are employed in new plastic products manufacturing, both for economic and environmental costs (Patel *et al.*, 2000). Environmental performance of the recycling of mixed plastics for non-plastics applications, such as concrete or plastic wood, is generally lower than other recycling options such as energy recovery (Brandrup, 2003; Baitz *et al.*, 2004).

(b) Chemical recycling

Chemical recycling processes are classified as tertiary recycling and use the traditional dissolution/reprecipitation methods and thermal conversion technologies such as pyrolysis, hydrogenation, and gasification for chemical and thermal decomposition. Chemical recycling is also known as "Feedstock recycling" (Lundquist *et al.*, 2001; Brandrup, 2003).

The dissolution/reprecipitation processes involve chemical reactions with an agent to separate the polymer constituents. Examples of dissolution/reprecipitation processes are hydrolysis, glycolysis, alcoholysis, methanolysis, hydroglycolysis, and aminolysis (Lundquist *et al.*, 2001; Zia *et al.*, 2007).

The products obtained from pyrolysis are different depending on the temperature applied during the process: generally at low temperatures are recovered monomers; at high temperatures pyrolysis processes yield gases, and distillates that can be applied as fuels, petrochemicals, and monomers (Mazumdar, 2002; Arandes *et al.*, 2003; Buekens, 2006).

Chemical recycling or chemical depolymerisation is particularly suitable for thermoset polymers (Goodship, 2001; Tukker, 2002; Cornell, 2003), because grinding them to a powder is not adding a value to recyclates. However, more common thermosetting resins are not suitable to be depolymerise into their original constituents, namelly epoxy and polyester (Pickering, 2006).

Achilias *et al.* (2007) refer the chemical recycling of plastic waste products, such as pipes, packaging film, bags and food-retail outlets, based on low-density polyethylene (LDPE), high-density polyethylene (HDPE) or polypropylene (PP), by using chemical methods, with a recovery index greater than 90% of the waste fraction. Measurements of the tensile mechanical properties and the FT-IR spectra of the samples before and after recycling showed that the product recycled was almost identical to the virgin polymer.

For some composite materials with plastics content, some intermediate processes between chemical and mechanical, are also applied notabily the "Vinyloop PVC-Recovery" process (Plinke *et al.*, 2000; Tukker, 2002)

(3) PVC

PVC is resistant when in soil, which means that it does not decomposes under landfill conditions. Furthermore, release of plasticizers that are not chemically bound to the product, such as phthalates, and heavy metals, these especially in acidic medium, should be taken under consideration (ARGUS, 2000).

As an alternative to landfill, incineration processes have also environmental burdens regarding discharges of combustion products, residues and effluents to the atmosphere, land, and water. Incineration of PVC releases acid gases such as Nitrogen Oxides and Hydrogen Chloride that requires additional neutralisation agents, affecting the quantity of residues generated by the gas treatment systems, especially of leachable chloride salts (Brown *et al.*, 2000; Bernard *et al.*, 2000).

Thus, an environmental concern with PVC landfill and incineration has made its recycling a current practice.

Mechanical recycling is generally applied to PVC recovery, both for rigid and soft PVC. Recycling efficiency depends on the potential to separate pure PVC, mixed PVC or mixed plastics fractions by separate collection, distinguishing between “high quality recycling” that can be used in the same PVC applications, and “low quality recycling” for downcycling purposes (Plinke *et al.*; 2000). Normally, “high quality” recycled PVC is used in the production of similar products to those originally discarded, such as extruded rigid and flexible window profiles and pipes.

Other construction PVC products are not suitable to be recycled for the same purpose due to their composition like composites and mixed plastics products, such as floorings produced from PVC pastes and cable insulation.

The potential for recycling PVC post-consumer wastes from construction is: 20-30% for flooring, 60-80% for pipes and fittings, and 50-60% for window profiles (Plinke *et al.*, 2000).

Post consumer vinyl flooring consists of uplifted flooring that has been removed for replacement. The key factors of recycling uplifted flooring as raw materials in the production of new floor are colour, contamination, and particle size. The recycling process starts by hand sorted to clean out any major piece of waste such as lumps of wood, and metal. Afterwards, vinyl flooring must be sorted by colour, and contaminants (e.g. asbestos, cadmium, older plasticizers, metals, and glues). Final product must ensure that contaminant substances are below threshold limit values, and that the contaminants cannot migrate to the surface. Finally, selected material has to undergo a size reduction by mechanical recycling processes, in order to produce a powered recyclate to be incorporated into a new product (Gardner, 2009). Yarahmadi *et al.* (2003) also stated the feasibility of mechanical recycling of old PVC floorings. Analysis procedures showed just an insignificant loss by evaporation of the original plasticizer content (about 10%) that should be added in PVC recyclate.

Another possibility for PVC recycling is chlorine recovery, of which PVC has a high content. For chlorine recovery as feedstock, chemical recycling methods are employed, such as incineration, steam gasification, gasification, and pyrolysis (Tukker *et al.*, 1999).

(4) Plastic fillers

Plastics, especially thermoset or contaminated ones, can be recycled as fillers in construction, with applications in concrete production or road construction. Fillers production is performed by regrinding plastics to suitable sizes and it is classified as secondary recycling (Mazumdar, 2002; Pickering, 2006).

Post-consumer plastic aggregates can be successfully and effectively used as a replacement of conventional aggregates, reducing bulk density of concrete in a range of 2.5 to 13.0 % (Siddique *et al.*, 2008). A decrease of compressive strength is related with the increase of the plastic aggregates content.

Recycling of Expanded Polystyrene (EPS) as a component for improving the durability of concrete is a common alternative to landfill. New developed recycling techniques based in thermal treatment methods may reduce the volume of waste EPS about 20 times by shrinking, increasing the average density from 10 kg/m^3 to 217 kg/m^3, in order to be used as aggregates in concrete production (Kan & Demirboga, 2009). Amianti & Botaro (2008) suggest impregnating concrete with EPS to reduce water permeability and porosity of pre-cast concrete surfaces and thereby improving its overall durability.

(5) Wood-plastic composites

Wood-plastic composites (WPC), also known as plastic lumber, are becoming a common substitute for wood lumber. Despite not being so strong and stiff as the wooden lumber, plastic lumber is presumed to weather better, does not splinter, rot or warp and does not require preservation treatments (Goodship, 2001; Carroll et al., 2003; OPTIMAT, 2003).

In building construction, wood plastic composites have a range of outdoor applications such as deck boards and components (see Figure 3.7), outdoor furniture, and window and door profiles, their main application.

Growing use of WPC is due to similar techniques of cut and fasteners with common wooden materials, and to the advantage resulting from not containing hazardous chemicals traditionally used for wood preservation, such as creosol and chromate copper arsenate (Chanda & Roy, 2007). Some limitations should be remarked such as energy requirements in production that are

3-4 times higher when compared to wood products manufacture, and the fact that they are nor suitable for structural applications (OPTIMAT, 2003).

WPC compounds are wood flour or wood fibres that acts as fillers, thermoplastic matrix materials (e.g. Polyethylene resins (HDPE, LPDE, LLDPE), Polypropylene resin, and Polyvinyl chloride resin), and additives such as coupling agents, light stabilizers, pigments, lubricants, fungicides, and foaming agents (OPTIMAT, 2003; Caulfield *et al.*, 2005; Chanda & Roy, 2007; Klyosov, 2007, Lee *et al.*, 2007).

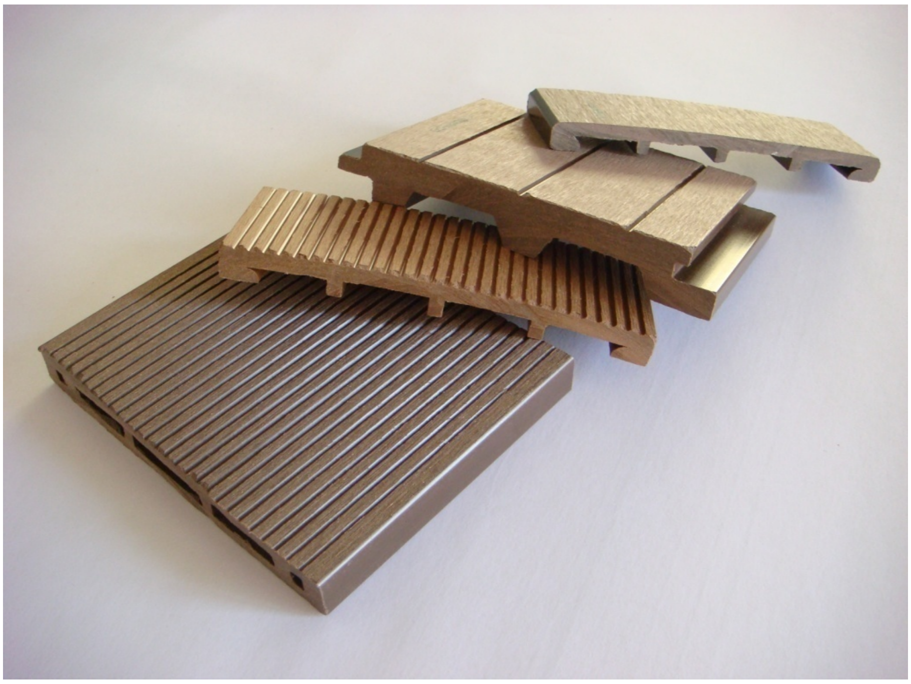


Figure 3.7. Wood plastic composite deck.

Although, wood material compounds are made usually by using by-products from forests companies such as lumber mills, furniture, millwork, and doors and windows manufacturers (Caulfield *et al.*, 2005), WPC products are also a promising possibility for recycling both wood chips or wood sawdust and post consumer HDPE and LPDE (Carroll *et al.*, 2003; Cui *et al.*, 2008).

Wood-plastic composites are pointed as suitable substitutes for good quality wood, reducing hardwood timber world demand (Carroll *et al.*, 2003; Cui *et al.*, 2008).

3.2.11 *Steel and stainless steel*

In general, steel is easily reclaimed and reused in new building works. Reuse of structural concrete is not maximized. Usually structural steel members are either partially or totally flame cut instead of being dismounted due to restricted removal of bolts (Hobbs & Hurley, 2001). Standardization of structural steel elements is an opportunity for total or partial reuse of steel members, but contamination and corrosion may be a significant barrier to reuse (Hurley *et al.*, 2002). Reuse of steel components should be preceded by standard tensile testing (Coventry *et al.*, 1999).

Reclaim of steel from demolished buildings for recycling is a common and ancient practice in the steel industry, both for structural sections and reinforcement steel.

New steel is often made in part or all from reclaimed steel scrap from different sources, reducing environmental impacts from steel production. As an example, comparing the primary energy burden, when compared with the use of only virgin raw materials, current recycling operation of stainless steel production represents a reduction of 33%, and 100% recycling of stainless steel production would represent a reduction of 66%, which is not actually possible due to limited availability of steel scrap (Johnson *et al.*, 2008). Recycling of stainless steel also decreases CO_2 emissions by 32% and 67% respectively.

3.2.12 *Non-ferrous metals*

Non-ferrous metals that are present in building construction are mainly aluminium, copper, zinc, and lead. These materials are employed usually as structural elements, coverings, cladding, roofing, windows and doors, frames, piping, ducting.

The high durability of non-ferrous metals makes their potential for reclamation very significant but there is little scope for reuse (Coventry *et al.*, 1999). However, non-ferrous metals are normally recycled as feedstock for production of new materials, after sorting and treatment processes. Recycling of non-ferrous metals has no effects on the quality of the metal produced, and reduces the amount of energy needed in the production of new materials (e.g. 95% energy reduction in aluminium production).

(1) Aluminium recycling

Due to its high performance, aluminium became the most common non-ferrous metal used in buildings, mainly for window and door frames, and piping.

Environmental impacts of aluminium are mainly caused by bauxite extraction and aluminium production. For example, to produce 1000 kg of Alumina it is needed 2639 kg of extracted bauxite and 21,000 MJ of energy input, and to produce 1000 kg of molten aluminium it is needed 1928 kg of alumina and 119,538 MJ of energy input (IAI, 2000).

Due to mass losses and energy requirements during the process, recovery of aluminium scrap becomes an important task for reducing environmental impacts from new metal production. Although the fraction of aluminium in construction and demolition waste is very small, around 1% or less according to Schlesinger (2007), the recovered material from buildings may represent an important part of total recovered aluminium scrap.

Aluminium is suitable for immediate reuse, mainly components with highly standardised systems and dimensions, such as window and door frames.

Metallurgical properties of aluminium enable scrap to be melted down and used to produce the same products along several life cycles without any loss in quality, what make its recycling economically attractive (Schlesinger, 2007). Extruded and rolled aluminium scrap may be recycled totality into aluminium ingots for the manufacturing of new aluminium products (IAI, 2000, 2003). According to GAA (1999), 85 % of the aluminium used in construction industry is already recycled. This figure will can be improved by guaranteeing that manufacturers take back used products.

Before melting, beneficiation of recovered aluminium must be made by applying to it several procedures (Schlesinger, 2007):

(i) Collection;
(ii) Shredding operations to reduce material volume;
(iii) Separation processes such as hand sorting, air classification, magnetic separation, Eddy-Current sorting, and heavy-media separation to remove undesirable products;
(iv) Thermal processing for decoating, paint removal, and sweat melting;
(v) Agglomeration processes to increase bulk density of recovered and treated scrap.

After beneficiation, aluminium scrap may be recycled by applying two different methods: melting or direct conversion (Gronostajski *et al.*, 2000).

Currently, most of the aluminium scrap is remelted in furnaces fired with fossil fuels or electricity. Traditional furnaces employ heat-transfer kinetics to melt the solid metal. Thus, inside the furnace heat is transferred from the heat source (usually burnt natural gas) by radiation and convection, or by direct contact of the hot gas.

Development of refining and purification technologies for molten aluminium have reduced the impurity levels of secondary aluminium, improving the quality of final products. At present, refining processes are applied both to new and secondary metal. Common impurities in molten secondary aluminium are:

(i) Hydrogen produced from a reaction between water vapour and the molten aluminium;

(ii) Reactive metals such as sodium, calcium, and magnesium that were captured by materials exposure to environment;

(iii) Solid particles suspended in molten aluminium;

(iv) Alloying elements such as copper, iron, manganese, silicon, and zinc.

Direct conversion of aluminium scrap uses extrusion processes to produce new aluminium ingots. This method reduces the amount of material losses from 54% to 5% when compared with traditional melting processes (Gronostajski *et al.*, 2000). At the same time, direct energy inputs are reduced from 16-19 GJ/t to 5-6 GJ/t, as also the number of processing operations, which allows reducing labour hours.

Coatings and complex alloys may turn recycling difficult or not economically feasible. Due to the growing use of aluminium alloys, new cost-effective recycling technologies and methods to separate aluminium alloys must be developed. Thus, the composition of aluminium scrap became an important issue to be considered, in order to make final products more or less suitable for high performance purposes (Dwight, 1999; Schlesinger, 2007).

3.3 *Recovery rates for selected building materials and components*

3.3.1 *Survey of recovery rates for building materials and components*

Presently, there is no significant number of studies on recovery efficiency or recovering rates of materials. Most studies on construction and demolition waste flows aims to establish or to predict reference percentages for different material wastes regarding the whole building mass.

Predictions on recovery rates for each material reclaimed in deconstruction activities is a fundamental step to evaluate deconstruction efficiency and consequently to determine its effectiveness.

A survey of published literature on recovery rates for building materials shows that there are different estimations for recovered and lost mass per material. Values for recovery rates were obtained by analyzing the building architectural configuration (Hurley, 2003) and by analyzing dismantling of buildings (Hobbs & Hurley, 2001; Erkelens, 2003; Newenhouse *et al.*, 2003; Chini & Nguyen, 2003; Schultmann, 2005; Crowther, 2000, 2005; Nakajima & Murakami, 2007).

Some studies present generic recovery rates for different building typologies, others presents recovery rates by material, and others focus on a particular material such as gypsum cardboard, steel or timber.

(1) Recovery rates for buildings

Drawing on the literature, the minimum generic recovery rates are around 70%. However, most studies point to higher recovery rates between 90 to 95% or higher, what seems to be optimistic as a generic estimation.

Hobbs & Hurley (2001) present recovery rates ranging between 95 to 97% for three dismantling case studies in the United Kingdom.

Erkelens (2003) presents the dismantling of a residential case study in The Netherlands where 71% of materials were reused, 20% recycled, 2% incinerated, and 7% discarded. The recovery rate was 93%.

Newenhouse *et al.* (2003) presents a 74% recovery rate for deconstruction of the Arts Center in Madison, Wisconsin. Only 4% of materials were suitable for reuse and 70.2% were suitable for recycling purposes. The amount of waste discarded was 25.8%. Recovered materials were composed of stone façade, concrete, metals, carpets, and tiles.

Hurley (2003) presented potential overall recovery rates for six case studies in the United

Kingdom. Overall recovery rates are in general higher than 90% (see Table 3.5).

Schultmann (2005) presents a comparative summary of recycling rates for 10 documented buildings that were dismantled in France and Germany between 1991 and 1998. Documented buildings include several types, such as residential, industrial, office, and school buildings. Recycling rate vary between 74.0 to 98.5% (see Table 3.6).

Table 3.5. Variable percentage potential for reuse/recycling for six case studies (Hurley, 2003).

	Multi-storey Housing	Prefab housing	Factory	Multi-storey offices	Factory	Hospital
Reuse	2.9	69.9	6.0	41.8	12.0	74.0
Recycle	89.9	23.9	89.0	27.3	86.0	24.0
Combustion	5.3	1.3		3.4	2.0	1.0
Inert landfiil				17.1		
Non-hazardous landfill	1.2	4.9	5	10.4		1.0
Hazardous landfiil	0.7					
Recovery rate (%) (reuse + recycling)	92.8	93.8	95.0	69.1	98.0	98.0

Table 3.6. Recycling rates for several building types in Germany and France (Schultmann, 2005).

Type of building	Number of buildings	Recycling rate (%)	Average recycling rate (%)
Residential	3	94.0	93.0
		90.0	
		95.0	
Industrial	6	94.0	93.0
		96.0	
		74.0	
		98,5	
		97,5	
		98.0	
School	1	98.0	98.0

(2) Recovery rates for building materials

In general, estimation recovery rates for selected building materials also point to be of around 90% of total mass.

Thormark (1998) presents generic values with high recovery rates, 85% for concrete and bricks, and 90% for timber (see Table 3.7.).

Table 3.7. Assumed percentages of materials discarded and recovered from dismantling (Thormark, 1998).

Materials	Recovered (%)	Discarded (%)
Concrete blocks	85	15
Brick	85	15
Timber	90	10

Crowther (2000, 2005) presents a more detailed study based on a survey of residential and office buildings in Australia (see Table 3.8.). In general, for residential buildings, recovery rates range between 70 and 80%, being roof tiles an exception, the recovery index of which is 50%. For office buildings, recovered rates vary between 25 and 95%.

Table 3.8. Percentages of materials and components by weight recovered from demolition (Crowther, 2000, 2005).

Materials and components	Residential building (%)	Office building (%) total (reuse – recyle)
Concrete	-	70 (0 – 70)
Concrete blocks	-	25 (25 – 0)
Brick	77	75 (60 – 15)
Aluminium	-	90 (0 – 90)
Tiles	-	75 (60 -15)
Structural steel	78	95 (15 – 80)
Steel reinforcing	-	50 (0 – 50)
Timber and timber products	79	50 (50- 0)
Roof tiles	50	-
Doors	71	-
Windows	73	-
Flooring	78	-

Blengini (2009) presents recovery rates for building materials used in a multi-storey housing in Italy ranging between 90 and 95% (see Table 3.9).

Table 3.9. Construction waste factor and recovery rates for selected building materials according to Blengini (2009)

Materials and components	Construction waste factor (%)	Recovery rate (%)
Concrete	7	93
Steel bars	7	93
Bricks	10	90
Mortar	10	90
Plaster	10	90
Paint	7	93
Mineral wool	7	93
Wood	7	93
Glass	7	93
Ceramic	10	90
Roof tiles	7	93
Plastic (PVC)	7	93
Aluminium	5	95
Copper	5	95

Other studies are focused on particular materials such as gypsum cardboard, steel, and timber.

For gypsum cardboard, Marvin (2000) indicates that 95% of new construction gypsum cardboard waste can be recovered. Thormark (1998) remarked the reusability of gypsum cardboard panels by proposing a reuse rate of 45%.

Considering steel, Durmisevic & Noort (2003) state that on average 83% of steel products are recycled, 14% are reused, and only 3% are discarded, what means a recovery rate of 97%.

Concerning timber recovery, Chini & Nguyen (2003) presented recovery rates of lightweight frame in good conditions buildings between 76 and 82%, drawing on a survey of residential buildings in Florida, United States.

Also in the United States, where structural wood frames are a common building system, Falk & McKeever (2004) estimate recovery rates of lumber ranging between 50 and 90%.

A more detailed survey of several timber houses in Japan, presented by Nakajima & Murakami (2007) estimated a 90% recovering rate for wood:

(i) Reuse of lumbers 2.00 m or longer: 45% reuse and 45% recycle as particleboard with 10% of the products lost in the trimming process;

(ii) Reuse of lumbers shorter than 2.00 m: no reuse and 90% recycle as particleboard with 10% of the products lost in the trimming process;

(iii) Recycling of wood waste: 90% recycle as particleboard with 10% of the products lost in the trimming process;

(iv) Recycling of mixed wood waste: 100% to landfill.

3.3.2 *Synthesis of recovery rates for selected building materials*

Recovery rates for selected building case studies shows that most values are above 90% (see Figure 3.8). Exceptions to main tendency are three lower values around 70%, which are not consistent with the main tendency. Thus, a median of 95.0% was established as a Recovery Rate of reference based on the survey, rather than an Average value.

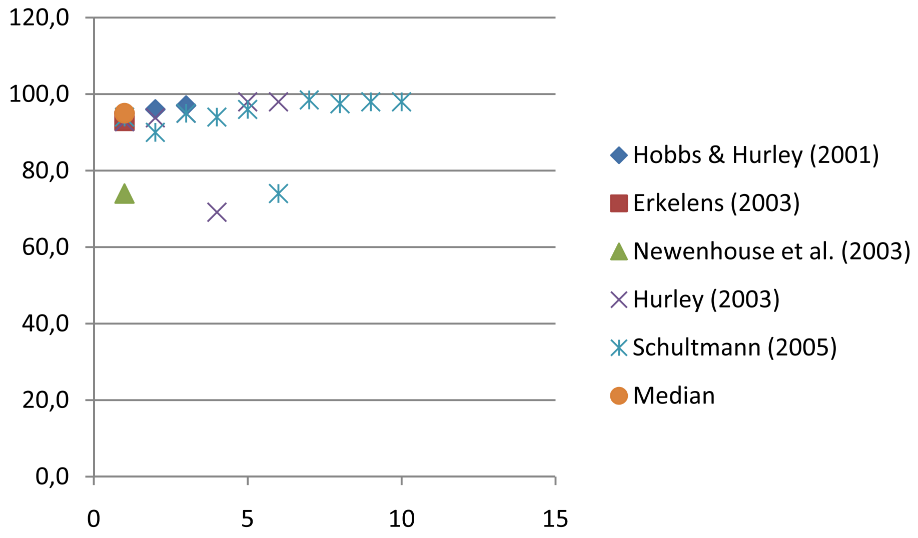


Figure 3.8. Recovery rates for selected case studies according several authors.

For selected building materials it is possible to observe that almost recovery rates are higher than 75% (see Figure 3.9). However, it is not possible to establish an overall criterion for all materials, in order to find an accurate reference value due to some factors:

(i) It is not possible to compare recovery rates for different materials because there are different building constraints for each kind of material;

(ii) Same materials present discrepant recovery rates, according to different sources, which affects average or median results;

(iii) For several materials there is just one value obtained from literature.

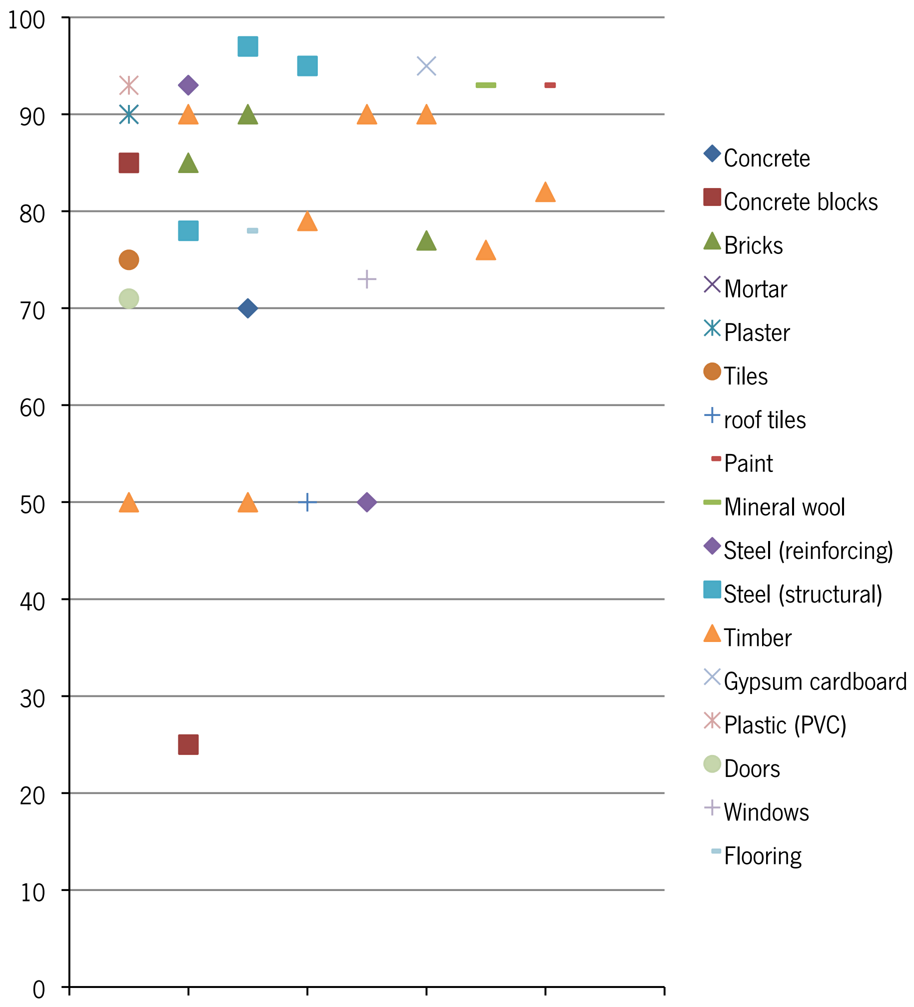


Figure 3.9. Recovery rates for selected building materials according several authors.

Thus, it was established that the recovery rate of reference would be the best value found for each material included in the survey (see Table 3.10). In general these values are not significantly lower than the recovery rate of reference for the buildings, which was 95%.

For those materials for which no data were available, the overall median for all other materials was considered as a reference, which was calculated as 90.0%.

Recovery rates also do not estimate partial values for reuse and recycling, since there is a lack of data, and recovery scenarios options depend on the quality of reclaimed materials.

Table 3.10. Estimated Recovery Rate (RR) for selected building materials.

Material/Component	Recovery Rate (%)	Data source	Best Estimated Recovery Rate (%)
Aluminium	95.0	Blengini (2008)	95.0
Bricks	77.0	Crowther (2000, 2005)	90.0
	85.0	Thormark (1998)	
	90.0	Blengini (2008)	
Concrete	70.0	Crowther (2000, 2005)	93.0
	93.0	Blengini (2008)	
Concrete blocks	85.0	Thormark (1998)	85.0
Copper	95.0	Blengini (2008)	95.0
Doors	71.0	Crowther (2000, 2005)	71.0
Flooring	78.0	Crowther (2000, 2005)	78.0
Glass	93.0	Blengini (2008)	93.0
Mineral wool	93.0	Blengini (2008)	93.0
Mortar	90.0	Blengini (2008)	90.0
Paint	93.0	Blengini (2008)	93.0
Plaster	90.0	Blengini (2008)	90.0
Plasterboard	95.0	Marvin (2000)	95.0
Plastic (PVC)	93.0	Blengini (2008)	93.0
Roof tiles	50.0	Crowther (2000, 2005)	93.0
	93.0	Blengini (2008)	
Steel (reinforcing)	50.0	Crowther (2000, 2005)	93.0
	93.0	Blengini (2008)	
Steel (structural)	95.0	Crowther (2000, 2005)	97.0
	78.0	Crowther (2000, 2005)	
	97.0	Durmisevic & Noort (2003)	
Tiles	75.0	Crowther (2000, 2005)	75.0
Timber and wood products	90.0	Falk & McKeever (2004)	93.0
	50.0	Crowther (2000, 2005)	
	79.0	Crowther (2000, 2005)	
	90.0	Thormark (1998)	
	90.0	Nakajima & Murakami (2007)	
	76.0	Chini & Nguyen (2003)	
	82.0	Chini & Nguyen (2003)	
	93.0	Blengini (2008)	
Windows	73.0	Crowther (2000, 2005)	73.0
	90.0		
Overall Median for RR *			

CHAPTER 4

ECO-THERMODYNAMICS OF BUILDING MATERIALS RECOVERY

4.1 *Eco-Thermodynamics*

4.1.1 *Thermodynamics, systems and material flows*

Thermodynamics deals with the problem of conversion of one form of energy to another, and its classical laws were formulated in the nineteenth century, by deduction from experimental observations. Within this approach, the two first laws are significant for the understanding of how materials and energy flow.

The First Law of Thermodynamics expresses the principle that the total amount of energy is conserved whatever energy conversion may take place (van Ness, 1969; Sato, 2004; Bokstein *et al.*, 2005).

This Law is extended to matter as 'The Law of Conservation of Mass', which states that, as for energy, the total mass of a closed system always remains constant (Crowell, 2007). Energy and mass cannot be created or destroyed, but only transferred from one system to another, i.e. transformed.

The Second Law can be stated in a variety of equivalent ways among which the following (Ganguly, 2008):

A transformation whose only final result is to transform into work heat extracted from a source which is at the same temperature throughout is impossible. (Kelvin statement)

or

A transformation whose only final result is to transfer heat from a body at a given temperature to a body at a higher temperature is impossible. (Clausius statement)

The relevance of the statement of the Second Law is that as energy flows through a closed system the energy available for work in that system decreases. In 1867, Clausius introduced the concept of a state property called Entropy as the low quality energy resulting from the Second Law statement. Entropy is a measure of the energy dispersal. A consequence of Entropy formulation is that as energy disperses over time, less concentrated energy is available to produce useful work (Exergy).

Formulations of Thermodynamics are based on closed systems. By definition, a closed system does not exchange energy or matter with the environment. On the other hand, an open system exchanges energy and matter with its surroundings, such as biological ecosystems do.

According to these definitions, the biosphere seems to be very much like a closed system, since it exchanges only energy with space, considering that matter exchange can be neglected. In open systems, rather than conserved, energy and matter can be accumulated or spent, and these exchanges equal the amount of the inputs less the amount of the outputs.

Thus, biological ecosystems are indeed coherent structures operating as open systems far from thermo-dynamical equilibrium and interacting with each other and their environment, taking advantage of all available means to resist externally applied gradients (Schneider & Kay, 1994, 1994a, 1995).

The nature analogy of Industrial Ecology principles emphasizes that this is also true for human society systems such as industrial systems and economics that in fact are open systems operating far from equilibrium, exchanging matter and energy across their boundaries in order to produce a set of commodities and by releasing waste and pollutants.

As matter is a finite component of the geobiosphere, in Earth all systems recycle and Earth itself operates as the ultimate recycling system. For examples, in nature, carbon, oxygen and nitrogen are recycled by the biosphere using solar energy, such as the photosynthesis process that occurs in plants. These recycling processes allow individual systems to grow by using energy to transforming matter, where the outputs of a system become the inputs of other system running at a different level.

At different scales, materials are stored and used within a system and recycled within the same or a different system. The biosphere is thus a network of continually recycling processes of materials alternating cycles of convergence and cycles of divergence (Brown & Buranakarn, 2003).

Cycles of convergence are those where materials gain ‘quality’, which means ‘structure’, as they become more concentrated, and cycles of divergence are those where materials become dispersed again in the environment after their potential has been used. Both cycles are driven by different forms of energy that interact with different forms or states of matter. As available energy degrades into low quality energy, more high-quality energy must be added to the system in order to keep it running and far from equilibrium.

In these processes or cycles, energy and matter are progressively degraded as long as energy and materials are used by the different systems. These transformations occur according to the Laws of Thermodynamics.

From the environmental point of view, this means that in cycles of convergence of materials, two aspects are relevant:

(i) All systems use available high quality energy to produce work and release the same amount of degraded energy; a clear example of this process is for instance the high entropy energy in form of heat released by blast furnaces in iron melting (low quality energy) that uses low entropy energy in the form of fossil fuels (high quality energy);

(ii) In production systems, stored materials in nature are concentrated in high quality materials with low entropy, as other waste materials and energy are released to the environment. An example would be what happens when a material is concentrated from a mineral ore.

Another relevant aspect is that at different stages of convergence cycles, concentrated materials are also released from production systems as waste by-products which act as contaminants to the environment because they are not easily dispersed. Such as volatile organic compounds, heavy metals, fly and bottom ashes and blast furnace slag.

From an environmental point of view, thermodynamics of materials may be clearly observed in Life-Cycle approaches. The Life Cycle of a material comprises all the stages of transformation since the extraction of raw materials to disposal of waste. Along the Life-Cycle, in each level of the transformation process, structured materials are produced as more energy and more materials are added into the process, and more outputs are produced in the form of released low quality energy and waste materials.

For example, mined bauxite is transformed in alumina, which is transformed in aluminium by electrolysis, which is extruded to be shaped in aluminium profiles by extrusion processes, which will be discarded after usage. All these processes require energy and materials inputs and produce degraded energy and waste materials.

The Second Law also explains natural depreciation of materials as they follow into equilibrium with their external environment, by changing their physical and chemical properties. Degradation of coatings by action of a heat source, i.e. light, and corrosion of metals exposed to air, are classical examples of the Second Law manifestation.

As observed in the previous examples, the role of the Second Law is also extended to building construction and materials durability. Graham (2003) emphasizes that Thermodynamics principles are applied to building materials due to the interactions with their external environment, which ultimately influences their durability.

4.1.2 *The Eco-Thermodynamics approach*

From en environmental point of view, depletion of non-renewable resources and increasing of environmental pollution are related with two main factors:

(i) Intensive harvesting of virgin materials needed to feed the economic and societal metabolism;

(ii) Low capability of natural recycling patterns to disperse concentrate materials in order to comply with the demands of economic systems, i.e. natural carrying capacity (Bringezu, 2002; EEA, 2005).

These assumptions lead to the next level of approach: the need to close materials loop in order to fulfil production demands and save non renewable resources.

Economic systems increased the burden of human activities by means of an intensive and increasing exploitation of natural resources and by defying the carrying capacity of nature to absorb the output of production and consumption network.

Such an assumption is also put forward by Ayres (1998) who states that in a larger system such as Earth, the first and second laws applied to matter imply that all the resources mined from the environment and processed, are and will be still present in the same amount but dispersed in the environment in the form of waste and pollutants. This leads to the concept of 'Eco-thermodynamics', by suggesting the role of the First and Second Laws for the explanation of the environmental impact of materials extraction, production, usage and wastage, and enhancing the role of reuse and recycling paths in environmental and economic systems to achieve a sustainable growth.

Despite the first and second laws imply the inevitability of unwanted by-products or waste arising from economic activities and consumption, these impacts may be reduced or avoided as industry turns from non-renewable resources to recycled resources, while recognizing the recycling potential of waste.

Furthermore, Ayres (1999) underlines this assumption by stating that there are no limits to growth as long as economy demands may be full-filled by the recycling of high quality waste.

The ever growing consumption of primary resources until 'total' depletion implies new production systems where the sources of matter will be the waste generated by products obsolescence and depreciation. However, the consumption of this 'waste resource' is limited by the quality of the waste itself, once the quality of the waste establishes the recovery pattern (e.g. reuse and recycle), and the technological products in which it will be used. Usually, these waste materials need an additional amount of primary materials to meet high quality standards (e.g. metals, glass) and always need new inputs of energy to be recovered.

Several authors have argued that total and perpetual recycling for an industrial society is impossible due to the Second Law of thermodynamics. On the contrary, Ayres (1999) refuted this assumption by remarking that the only obstacle for continuing recycling is the availability of Exergy to keep the systems running. In a stable recycling system, the quantities of active and inactive resources would be constant, and therefore the outflows and inflows of each kind balanced. However, the efficiency of mass recovery and the amount that turns back into the system, due to entropy, will never be balanced and unwanted materials must be stored again in order to be returned later to the active system (see Figure 4.1).

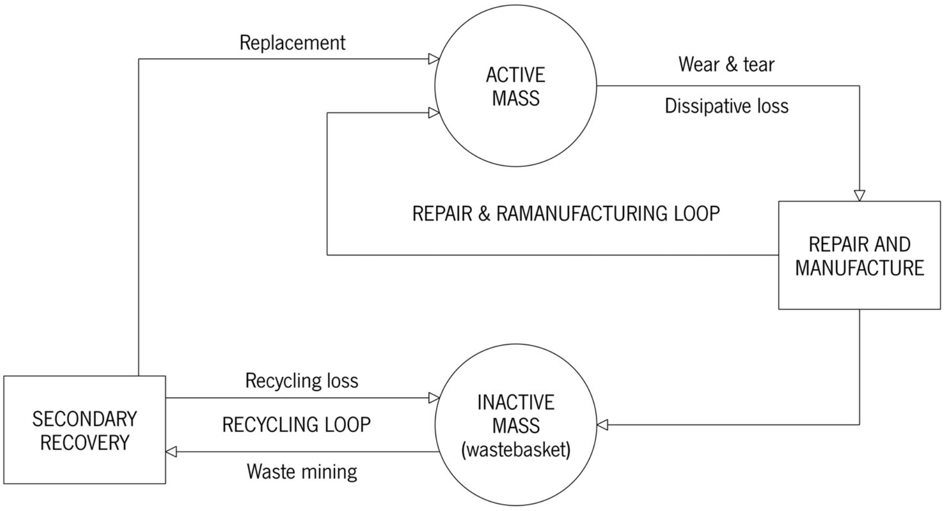
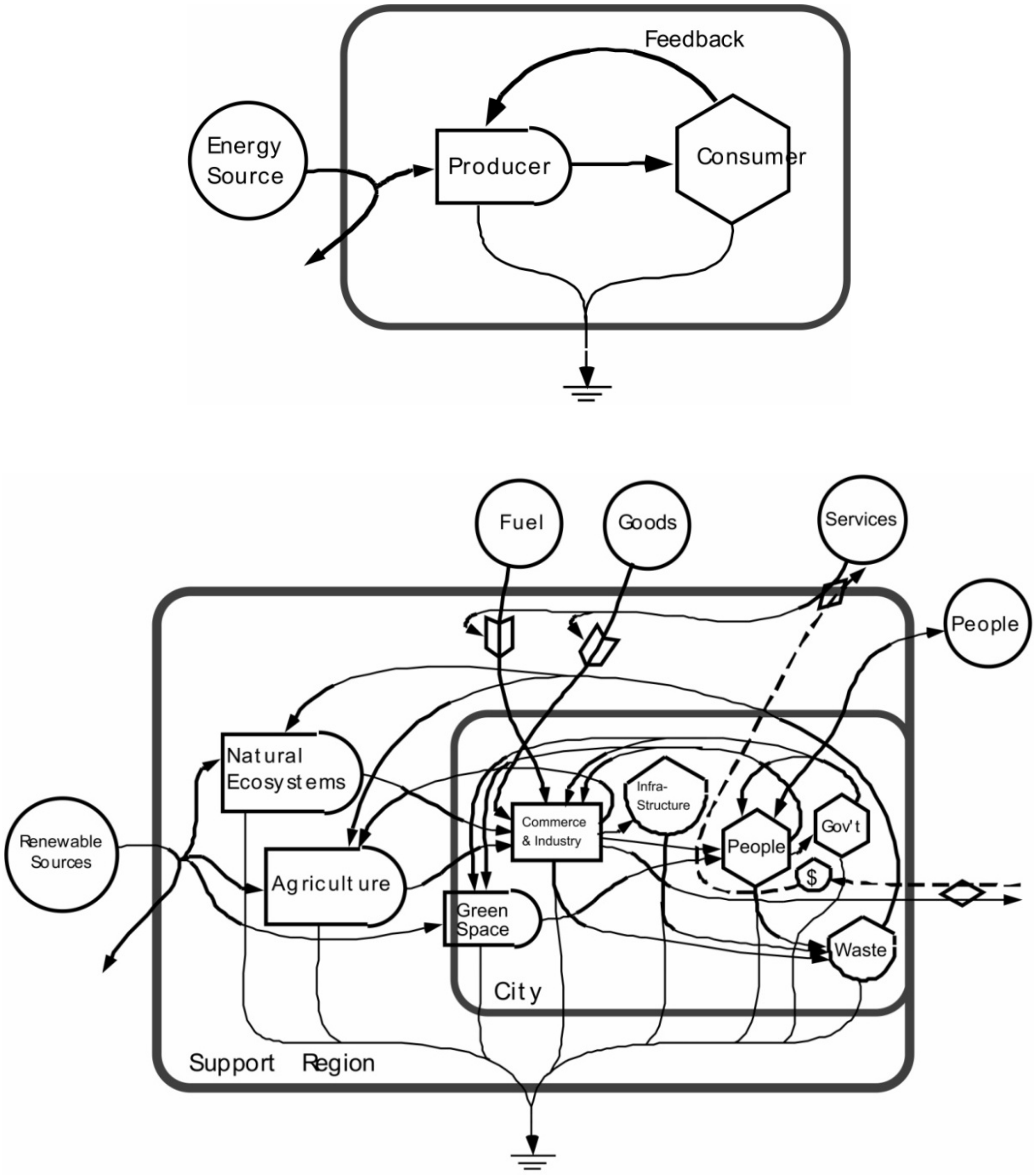


Figure 4.1. A complex stable recycling system (adapted from Ayres, 1999).

4.2 *Energy systems analysis*

4.2.1 *Methodologies for energy systems analysis*

Systems are by definition a group of parts which are connected and work together. The placement of the system's boundaries is related to its complexity. The greater the scale of analysis, the more complex becomes the system (see Figure 4.2). Systems analysis breaks apart its constituents in order to understand the overall behaviour.



a)

b)

Figure 4.2. Complexity of systems: a) a simple ecosystem; b) a city & support region system, from Odum (2001).

Several methodologies are used to analyse energetic systems, such as Exergy Analysis, Embodied Energy Analysis and Emergy (spelled with an 'M') Analysis. These tools are commonly applied with the purpose of evaluating environmental impacts, systems efficiency, or resources management in different fields of production. Other tools such as Life Cycle Assessment (LCA) are also grounded in systems analysis principles as an approach to understanding how elements in the system interact.

In Exergy Analysis theory, 'Exergy' accounts for the amount of available energy or utilizable energy, or maximum potential work, distinguishing it from energy which is unavailable. The common user of the word "energy" would use instead, if accurate, the word "Exergy" that is the correct definition of the potential to cause change (Barclay, 1995). Heat can only be converted into useful work if there is a temperature gradient, such as that between the Earth and Sun that drives the natural processes in our planet, as for example the weather and photosynthesis (Ayres & Warr, 2005).

Exergy expresses also energy's ability to be converted into other kinds of energy, and its capacity for doing work that can be used within a system of energy, in normal Earth environments (Sato, 2004). Thus, Exergy can be used as a measure of the potential work embodied in energy and materials as a general measure of technical efficiency and a first-order approach to the environmental impacts of systems operating (Costa *et al.*, 2001; Ayres & Warr, 2005).

For further studies, examples of Exergy Analysis may be found in literature related with applications as a measure of sustainability (Gong & Wall, 2001; Dincer & Rosen, 2005), in the evaluation of processes efficiency (Ayres, 1997, 1998; Wall, 1998; Ayres & Warr, 2005; Castro *et al.*, 2007) and of the life cycle of industrial materials such as steel (Michaelis *et al.*, 1997; Ayres et al., 2002; Costa *et al.*, 2001). In the literature, applications of Exergy Analysis to building construction or building materials are not significant and relevant example was not found.

In construction, Embodied Energy is used as an indicator of the environmental impact of materials (Thomas, 1996; Woolley *et al.*, 1997; Viljoen & Bohn, 2001; OECD, 2003; Sassi, 2006). This assumption is made by relating the energy intensity required in a system to produce a commodity with the "intrinsic" emissions released to the atmosphere (mainly CO_2) due to the use of that energy the source of which is generally considered as being fossil fuels. The higher the embodied energy of a material, the higher the release of emissions to the atmosphere, and thus greater is the contribution for the greenhouse effect and for climate change.

The Emergy theory (spelled with an 'M') was developed by H. T. Odum, an environmental ecologist from the University of Florida, for the past 35 years until his death in 2002. His theoretical approach and methodology are extensively explained and discussed in Odum (1996) where Emergy is defined as being:

...the available energy of one kind previously used up directly and indirectly to make a service or a product.

Emergy Analysis recognizes hierarchy patterns in energy and in materials (Odum, 1996; Brown *et al.*, 2004), by analyzing the contribution of both natural and man-made systems for products delivery within a same unit. Emergy enhances 'quality', i.e. structure, as a property of materials and energy.

Emergy has been applied to a great variety of subjects, such as energy evaluation, sustainability, ecosystems, agriculture, and materials. Emergy has been also applied to building construction and building materials and several environmental indicators have been proposed (Buranakarn, 1998; Brown & Buranakarn, 2000, 2003; Huang & Hsu, 2003; Meillaud *et al.*, 2004; Pulselli *et al.*, 2007).

4.2.2 *Emergy Analysis and Embodied Energy Analysis: a brief comparison*

A comparison between Embodied Energy Analysis and Emergy Analysis is discussed with the purpose of evaluating the analytical tool suitable for achieving the goal of the current research. Several studies compare Emergy and Embodied Energy analysis (Brown & Herendeen, 1996; Herendeen, 2004), and Emergy and Exergy analysis (Jorgensen *et al.*, 1995; Bastianoni & Marchettini, 1997; Ulgiati, 2000; Jorgensen *et al.*, 2004; Sciubba & Ulgiati, 2005; Bastianoni *et al.*, 2006).

Embodied Energy is quite often used as a measure of building materials sustainability, and applications of Emergy Analysis to buildings and building materials have also been proposed. Therefore, a closer look on the subject becomes important to understand the advantages and disadvantages of these methods for the development of a tool for the analysis of the effectiveness of building materials recovery.

Embodied Energy Analysis is the method employed to determine the energy required directly and indirectly for a system to produce a good or a service. Thus, the Embodied Energy of a product describes the amount of energy consumed by all the processes within a production system, from the acquisition of raw materials to product delivery, including mining, harvesting, manufacturing of materials and equipment, and transportation operations. By aggregating all these energy flows, Embodied Energy describes the energy intensity of a product.

On the other hand Emergy analysis uses the thermodynamics basis of all energy and materials used in the working processes that generate a commodity or a service, by converting those flows in units of the same type, the Solar Emjoule (seJ). Thus, Emergy measures value of both energy and material resources within a common framework. In Emergy embodiment of an energy source or a material are included the services provided by nature, which are normally kept outside by other systems analysis tools (Brown *et al.*, 2000).

To understand the value of energy and materials, the Emergy approach recognizes the hierarchical organization of systems according to the Second Law of Thermodynamics, and as a consequence energy and materials placed in the higher level of the systems hierarchy have a superior value, i.e. higher Emergy per unit.

(1) System analysis boundaries

Embodied Energy Analysis includes both direct and indirect effects of energy intensity use, by including also the energy required outside the main production system, such as transportation, manufacturing of secondary materials, and facilities.

In Emergy Analysis calculations not only direct and indirect flows are accounted, but also the work of the geobiosphere is included.

(2) Embodied energy per mass and Emergy per unit

Embodied Energy Analysis often uses pre-calculated energy intensities based on the assumption that those values may be applied generally (Herendeen, 2004).

Also, Emergy Analysis often uses pre-calculated values for Emergy per unit of input, i.e. Emergy per Joule, Emergy per gram, or Emergy per monetary currency.

In both cases, the use of pre-calculated values makes systems analysis less complex and saves working time.

(3) Renewable and non- renewable resources

Embodied Energy analysis can include renewable sources of energy as long they are kept separate from non-renewable sources. Only by keeping those flows in separate would to be possible to calculate direct and indirect pollution releases using the Embodied Energy analysis framework, such as direct and indirect CO_2 releases within a given process.

Emergy theory recognizes differences between renewable and non-renewable resources, by using the same unit for measuring energy hierarchy. As all flows are kept separate for accounting purposes, renewal and non-renewable resources may be easily aggregated for the calculation of environmental ratios such as the Environmental Loading Ratio (ELR = (Purchased resources + Non renewable resources) / Local renewable resources) (Ulgiati & Brown, 1998).

(4) Environmental load

Viljoen & Bohn (2001) state that embodied energy is an important reference, because the use of non-renewable energy sources is the principal reason for environmental degradation. Environmental degradation is caused, among others, by atmospheric pollutants, such as CO_2 emissions derived from the use of fossil fuels, which is contributing to global warming. This assumption is also put forward by Thomas (1996), Woolley *et al.* (1997) and Sassi (2006). However, the idea may be quite misleading because a turning point to renewable energy sources would decrease environmental impacts of production systems based on fossil fuels.

If the energy used is generated by wind or hydro-power instead of fossil fuels, such as coal or oil, the environmental impacts are expected to decrease, but Embodied Energy would account for this renewable energy flows in the same manner as non-renewable sources, i.e. according to their heat content.

While Embodied Energy uses heat as a reference to describe the environmental load of materials, Emergy analysis focuses on ‘quality’ as an indicator of energy and materials hierarchy, and thus their environmental load.

This question is also addressed by Brown & Herendeen (1996) by remarking that

> *The basic motivation for energy analysis is to quantify the connection between human activities and the demand for this important resource.*

As Emergy recognizes hierarchical principles in materials and energy properties, higher values of Emergy per unit for energy and materials indicates their level of convergence along the different stages of production. More concentrated forms of energy and materials would have a higher impact when released to the natural environment, i.e. it would be more difficult to disperse such materials in the geobiosphere.

Brown & Herendeen (1996) also remark that Embodied Energy Analysis does not have an optimizing principle and does not quantify the environment's role in absorbing and processing pollution.

(5) Discussion

The main difference between Emergy Analysis and Embodied Energy Analysis may be pointed as being the following: Emergy is defined as the energy of one kind (usually solar energy) that is required to produce something; i.e. solar, tidal, chemical potential energy, fuels or electricity are expressed in the equivalent solar energy required to produce them, while Embodied Energy Analysis uses heat energy and does not distinguish environmental aspects among energy sources and does not include the so called environmental energy sources, i.e. solar, crustal heat and tidal energies that drive the global earth system.

Emergy introduced the concept of energy 'form', stressing that not all energies are of the same quality, while Embodied Energy Analysis does not recognize quality differences in energy sources.

From an Embodied Energy perspective, it is quite obvious that building materials produced from renewable resources, such as wood, are not as energy intensive as those obtained from non-renewable resources. However, the Embodied Energy of a product does not allow straightforward analysis of the environmental burden of the process by which it was produced, just by addressing emissions to atmosphere to energy intensity use, as suggested by Viljoen & Bohn (2001), Gao *et al.* (2001) Reddy & Jagadish (2003). The amount of emissions released directly or indirectly from a system due to energy use intensity may be estimated later by using the Energy analysis framework, as long as renewable sources of energy are kept distinct from non-renewable sources of energy during the analysis procedures.

On the other hand, Specific Emergy highlights the environmental burden of a material, by recognizing the degree of dissipation of matter and energy required for concentrating or producing it, enhancing the importance of closing the loop of high quality materials. Such highly concentrated materials are supposed to be more difficult to dissipate in nature by biogeophysical processes.

A comparison between Embodied Energy and Specific Emergy of selected building materials highlights how both methods deals with flows accounting (see Table 4.1):

(i) A correspondence between the highest energy intensive materials and materials with higher Emergy per mass, what is explained by the amount of energy (work) required to concentrate them, since they are not abundant in nature;

(ii) Recycled materials show a reduction of energy intensity for Embodied Energy per mass because recycling processes are less energy intensive, while Emergy per mass increases because the memory of the flows used to produce the recovered material is kept (see Emergy recycling accounting later in this chapter);

(iii) In Emergy per gram of recycled materials, their convergence and environmental value is kept.

Table 4.1. Comparison between Embodied Energy and Specific Emergy for selected building materials.

Building Material	Embodied Energy (1) (MJ/kg)	Specific Emergy (seJ/g)
Aluminium (primary ingot)	191.0	45.0 E+09 (3)
Bricks	2.5	4.23 E+09 (2)
Ceramic tiles	2.5	3.32 E+09 (3)
Concrete	1.3	3.40 E+09 (3)
Glass	15.9	7.69 E+09 (2)
Steel (primary ingot)	32.0	4.15 E+09 (2)
Steel (secondary ingot)	10.1	4.41 E+09 (2)

Notes:

(1) Source: University of Wellington, Centre for Building Performance;
www.vuw.ac.nz/cbpr/resources/index.aspx; acceded on April 04 2005

(2) Source: Buranakarn (1998)

(3) Source: This study

While Embodied Energy is just a measure of the energy intensity of a material or product, Emergy expresses the work that was required, both natural and human, to concentrate elements and compounds which are not found in concentrated forms in the environment. Emergy per gram indicates materials concentration and environmental value, and not just their energy intensity. A net benefit analysis according to this assumption is more embracing of both nature and human contributions.

In spite of the similitude of both frameworks, by keeping the quality of recycled materials to produce work and their environmental value, Emergy Analysis proves to be a more suitable methodology to address the net benefit analysis of materials recovery, when compared with Embodied Energy Analysis. This assumption is quite relevant when materials with different quality are compared in a net benefit analysis.

4.3 *Emergy Analysis*

4.3.1 *The Emergy theory: general principles*

Emergy theory is grounded in two main principles:

(i) Thermodynamics and general systems theory;

(ii) *The real wealth of the environment comes from the work of the geobiosphere* (Odum, 1996).

These two principles recognize the processes by which energy and matter flows in our planet, and the role of the environment as the largest scale system.

According to the Second Law, Emergy accounting recognizes energy hierarchy principles and materials concentration and dispersion processes or cycles. Thus, Emergy measures quality differences between forms of resources and energy in open systems (Brown & Buranakarn; 2003; Brown *et al.*, 2004; Brown & Ulgiati, 2004).

In general, a product contains available Energy that can be released in order to produce work and be measured as the heat (joules or calories) generated during energy conversion processes. However, Emergy is not energy and so the quantities represented in Emergy Analysis are not energy and therefore do not behave like energy.

When a system is evaluated using Emergy Analysis, the quantities represented are not energy, but the ‘memory’ of the solar energy used to make it (Brown & Herendeen, 1996). This technique allows analysing a system whereby different flows such as energy, materials, services, information, or money, are quantified on the common basis of their solar equivalent energy: the solar emjoule (abbreviated seJ). Emergy measures the thermodynamic and environmental values of energy and resources.

Therefore, Emergy is an expression of the required investment or work from both nature and human societies to generate a product or a service (Odum, 1996). The higher the required investment, the higher the quality assigned to the produced item.

The use of Emergy, allows comparison between different materials, energy kinds and processes, by using a quantitative measure to express their different qualities or forms which are not directly compared by other methodologies.

By introducing the concept of Emergy, Odum changes the focus from the relation between human activities and fossil fuels to the relations between human activities and the environment. Therefore, the Emergy of a given product is also a measure of the planet's self-organisation in making it. Thus, Emergy accounting provides indicators that expand the evaluation process to the global scale of the planet (biosphere), by linking local processes to the global dynamics of the planet and providing a method to adapt human driven processes to natural processes (Sciubba & Ulgiati, 2005).

Emergy is also applied to monetary flows, by converting money payments into Emergy units. In a system, Emergy of monetary flows represents the Emergy that is in the purchased services. Emergy per money unit represents the relation of the amount of Emergy supporting a nation economy and the amount of money circulating, i.e. total Emergy use of a nation by its gross economic product.

The Emergy per monetary unit varies by country and is useful to evaluate service inputs given in monetary units. This principle is widely discussed in Odum (1996).

4.3.2 *Energy hierarchy*

Energy hierarchy is the core concept of Emergy theory, and was proposed as a fifth energy law by Odum (1996, 2000a), that follows from the second law and the fourth energy law (Lotka, 1922) that states the self organization of systems to achieve maximum power. This concept leads to the notion of energy quality, which means that different forms of energy have different abilities to do work. Such differences must be accounted for. This concept is also extended to materials circulation in the biosphere.

In energy transformation, available energy of one kind is required in a transformation process to produce a unit of energy of another kind (see Figure 4.3), comprising the idea of an energy hierarchy network, where the output of an energy transformation congregates energy to produce an even smaller output at the next higher level (Odum, 1996) (see Figure 4.4).

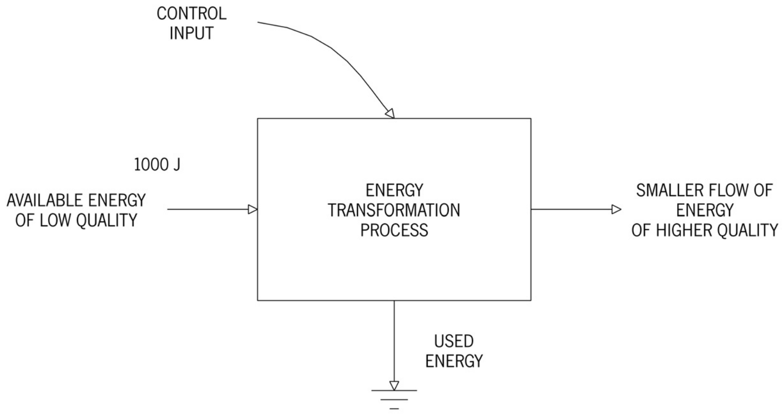


Figure 4.3. Energy transformation process.

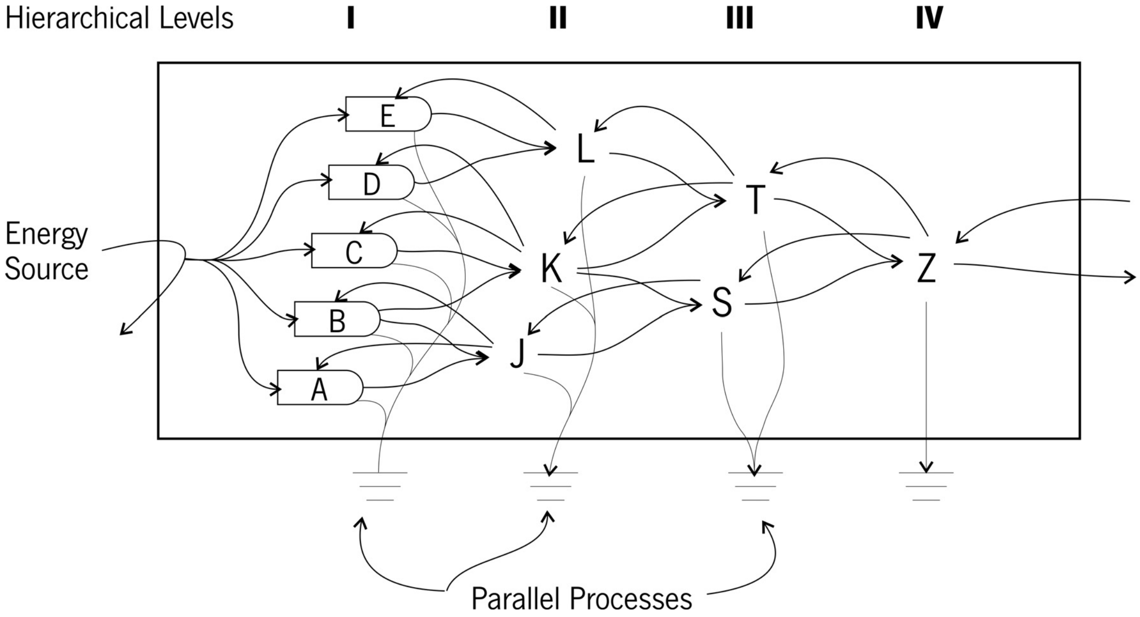


Figure 4.4. Hierarchical network of energy transformation processes (Odum, 1996).

As energy, also environment and economy can be described according the successive energy transformations that are required to keep the systems running (Odum, 2002; Brown & Ulgiati, 2004; Brown *et al.*, 2004).

Thus, according to the principles of energy hierarchy in which Emergy theory is grounded, Odum introduced the concept of Transformity (Odum, 1996):

Solar Transformity is the solar Emergy required to make one joule of a service or product. Its unit is solar emjoule per joule (seJ/J). A product's solar transformity is its solar Emergy divided by its energy.

By definition, solar Transformity is a measure of the hierarchy of energy and represents the energy investment per unit of product, which is the measure of how available energy (Exergy) is transformed and degraded. Transformity is a measure of Emergy intensity, and the concept is applicable not just to energy, but also to matter, services, and information.

Therefore, several types of Emergy intensity may be presented (Brown & Ulgiati, 2004):

(i) Transformity, defined as the Emergy input per unit of available energy (exergy) output, usually expressed as Solar Emergy per joule (seJ/J);

(ii) Specific Emergy, defined as the Emergy input per unit mass output, usually expressed as Solar Emergy per gram (seJ/g);

(iii) Emergy per monetary unit, defined as the Emergy supporting the generation of one unit economic product (currency), usually expressed as Solar Emergy per a given currency (e.g. seJ/$, seJ/€);

(iv) Emergy per unit labour, defined as the amount of Emergy supporting one unit of labour directly supplied to a process, usually expressed as Solar Emergy per time (e.g. seJ/year, seJ/h), or Solar Emergy per money earned (seJ/$) or even as Solar Emergy per energy spent by labours (seJ/J).

According to energy hierarchy, Solar Transformity increases as available energy decreases (see Figure 4.5). The lowest level of energy form is solar energy, and so the Solar Transformity of sunlight is by definition 1 seJ/J.

To establish the basis for all Transformity calculations, the Emergy of the three sources of the Earth energy is considered: solar energy absorbed, crustal heat sources, and tidal energy. This Emergy flow is used as a baseline reference for further Emergy calculations, according to the principles of energy hierarchy. Details on calculations of the Emergy of Earth are given in Odum (1996) and the Emergy flow of Earth was calculated as being 9.44 E+24 seJ/yr.

The initial baseline for the Earth Emergy was later reviewed by Odum (2000) and a new baseline of 15.83 E+24 seJ/yr was calculated.

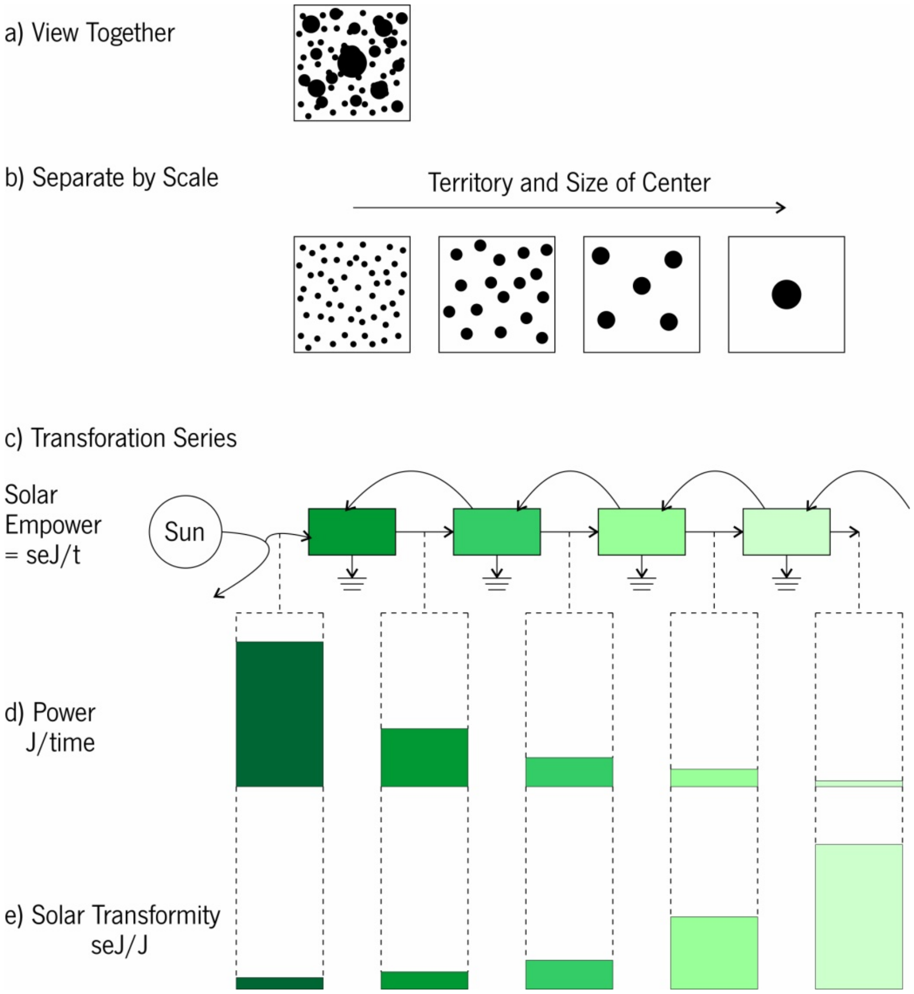


Figure 4.5. Energy transformation hierarchy according to Odum (1996). (a) Global spatial view. (b) Spatial view of units and their territories. (c) Aggregation of energy networks into an energy chain. (d) Bar graph of the energy flows for the levels in energy hierarchy. (e) Bar graph of solar transformities.

Materials transformation is dependent on the flows of energy. Energy makes materials circulate in nature either in the same form or by changing their form. Materials circulation and energy flows are both essential for a system to run. This is the same as saying that materials are “coupled” with energy transformations (Odum, 2002), because systems are able to manufacture useful products through materials incorporation, but that wouldn’t be possible without available energy.

According to the Second Law of Thermodynamics, materials that are concentrated tend to disperse in the environment (depreciation) as they move to thermodynamical equilibrium by means of heat or chemical reactions. Later the same materials are stored again in the environment by means of natural recycling processes (see Figure 4.6).

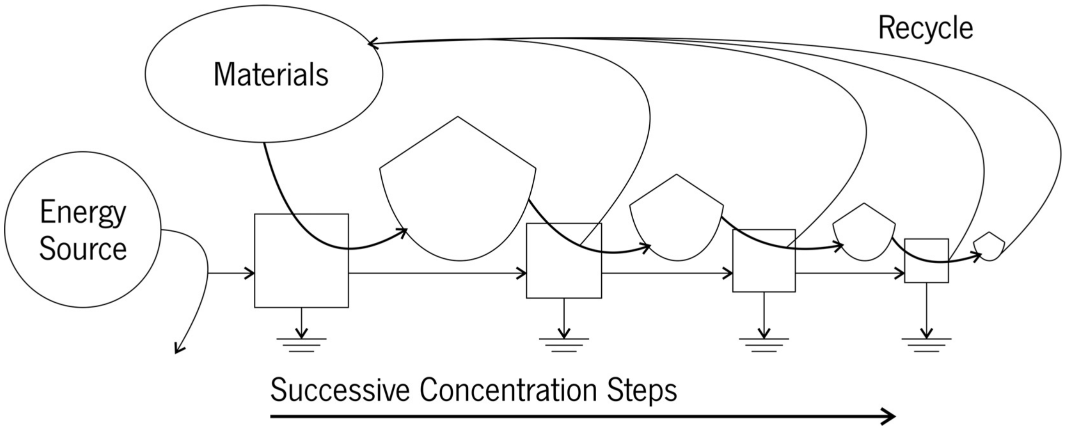


Figure 4.6. Systems diagram showing decrease of materials with each step in concentration according to Odum (1996).

In order to concentrate materials, energy inputs are needed. In metals production this process is very clear: several inputs of available energy are added to the system to concentrate the metal dispersed in the mineral ore, in a form in which it is not present in nature, such as aluminium or iron. Emergy of materials indicates the energy role of materials. As a principle, it takes more Emergy to concentrate materials that are scarce in the geobiosphere, such as gold, hydrogen, silver, and lead.

Transformity and Specific Emergy are not constants and do not have the same value for the same product or form of energy everywhere. Transformity and Specific Emergy values are the result of the chosen path to produce the same product. A more efficient production system would input less available energy and reduce outputs generation.

4.3.3 *Emergy accounting procedures and representation*

Emergy analysis follows the principles of systems analysis, as applied for example in Life Cycle Analysis, or in the framework of Life Cycle Assessment methodologies.

Emergy accounting framework is composed by a set of steps that comprises system diagramming, flows accounting and calculation procedures.

In the first step, an energy systems diagram must be drawn using the energy systems symbols shortly described in Figure 4.7. This diagram combines the information gathered about the system under analysis. If available, detailed Life Cycle Inventories are a good source of the required information. Emergy diagramming describes the relationships between components and flows that cross the system's boundary.

For the definition of the Emergy diagram, a set of procedures must be undertaken:

(i) Defining the system's boundary to determine which inputs must be considered, and it is represented by a rectangular frame where sources and systems components are drawn using systems symbols;

(ii) Describing the main components that are part of the process under analysis, such as materials, energy kinds, operations, and storages;

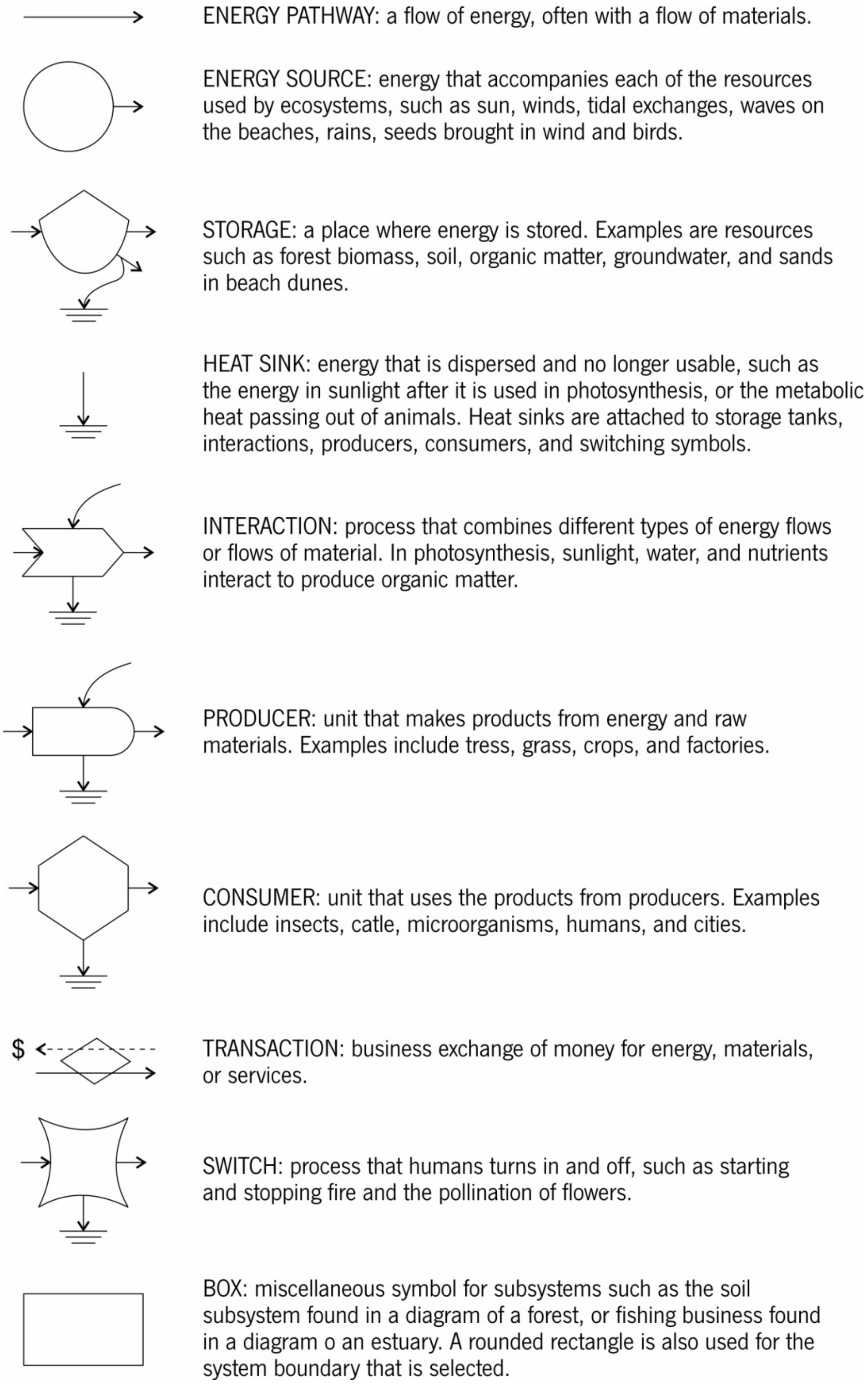
(iii) Describing the relationships between the items that are supposed to be part of the system, such as production processes, consumption processes, feedback loops, flows, and interactions;

(iv) Drawing the system diagram including all the collected information, by using the symbols listed in Figure 4.7.

An important aspect in Emergy diagramming, is that sources and systems components have to be placed in a hierarchical order of quality (Transformity) from left to right.

Flows in this diagramming stage are quantities described in energy units or mass units. The input units must be converted into reference units such as joule (J) for energy and gram (g) for mass.

The second step is to build the Emergy evaluation tables by using the information described in the system diagram, in order to calculate all the Emergy flows within the system. The typical layout of an Emergy evaluation table is presented in Table 4.2.



ENERGY PATHWAY: a flow of energy, often with a flow of materials.

ENERGY SOURCE: energy that accompanies each of the resources used by ecosystems, such as sun, winds, tidal exchanges, waves on the beaches, rains, seeds brought in wind and birds.

STORAGE: a place where energy is stored. Examples are resources such as forest biomass, soil, organic matter, groundwater, and sands in beach dunes.

HEAT SINK: energy that is dispersed and no longer usable, such as the energy in sunlight after it is used in photosynthesis, or the metabolic heat passing out of animals. Heat sinks are attached to storage tanks, interactions, producers, consumers, and switching symbols.

INTERACTION: process that combines different types of energy flows or flows of material. In photosynthesis, sunlight, water, and nutrients interact to produce organic matter.

PRODUCER: unit that makes products from energy and raw materials. Examples include tress, grass, crops, and factories.

CONSUMER: unit that uses the products from producers. Examples include insects, catle, microorganisms, humans, and cities.

TRANSACTION: business exchange of money for energy, materials, or services.

SWITCH: process that humans turns in and off, such as starting and stopping fire and the pollination of flowers.

BOX: miscellaneous symbol for subsystems such as the soil subsystem found in a diagram of a forest, or fishing business found in a diagram o an estuary. A rounded rectangle is also used for the system boundary that is selected.

Figure 4.7. Symbols of the energy systems language, according to Odum (1996).

Table 4.2. Layout of a typical Emergy accounting table.

C1	C2	C3	C4	C5	C6	C7
Note	Item	Unit	Data	Unit Solar Emergy	Reference for Unit Solar Emergy	Solar Emergy = C3 x C5
1	XXX	(J/yr) or (g/yr) (J) or (g)	XXX	(seJ/unit)	XXX	(seJ/yr) or (seJ)

The following data must be assigned to each column:

(i) Column 1 is for the line number and the reference of the footnote in the table where all the sources and calculations summarized in the Emergy evaluation table are included;

(ii) Column 2 is for the name of the item input into the system;

(iii) Column 3 is for the unit in which the amount or flow of the item is presented;

(iv) Column 4 is for the raw data of the item in unit according to what is described in column 3;

(v) Column 5 is for the Emergy per unit (e.g. Transformity or Specific Emergy) used for calculations, either picked from previous studies or calculated apart;

(vi) Column 6 is for the source of the Emergy per unit; this column is optional and such information may be inserted in the table footnotes;

(vii) Column 7 is the solar Emergy of a given item, calculated by multiplying Column 3 by Column 5.

As general procedures, the input raw data of flows of energy or materials, expressed as joules or grams, are converted to Emergy units (seJ) by multiplying the inputs of different energy kinds and materials by their Transformity and Specific Emergy.

After being converted to Emergy units, all the inputs are summed up into a total Emergy flow that drives the system or a total Emergy storage needed to produce a commodity, depending on the input data and on the aim of the study.

By dividing the total Emergy flow or Emergy storage by the energy or the mass content of the functional unit used as reference in the system, values for Transformity or Specific Emergy are obtained (see Figure 4.8).

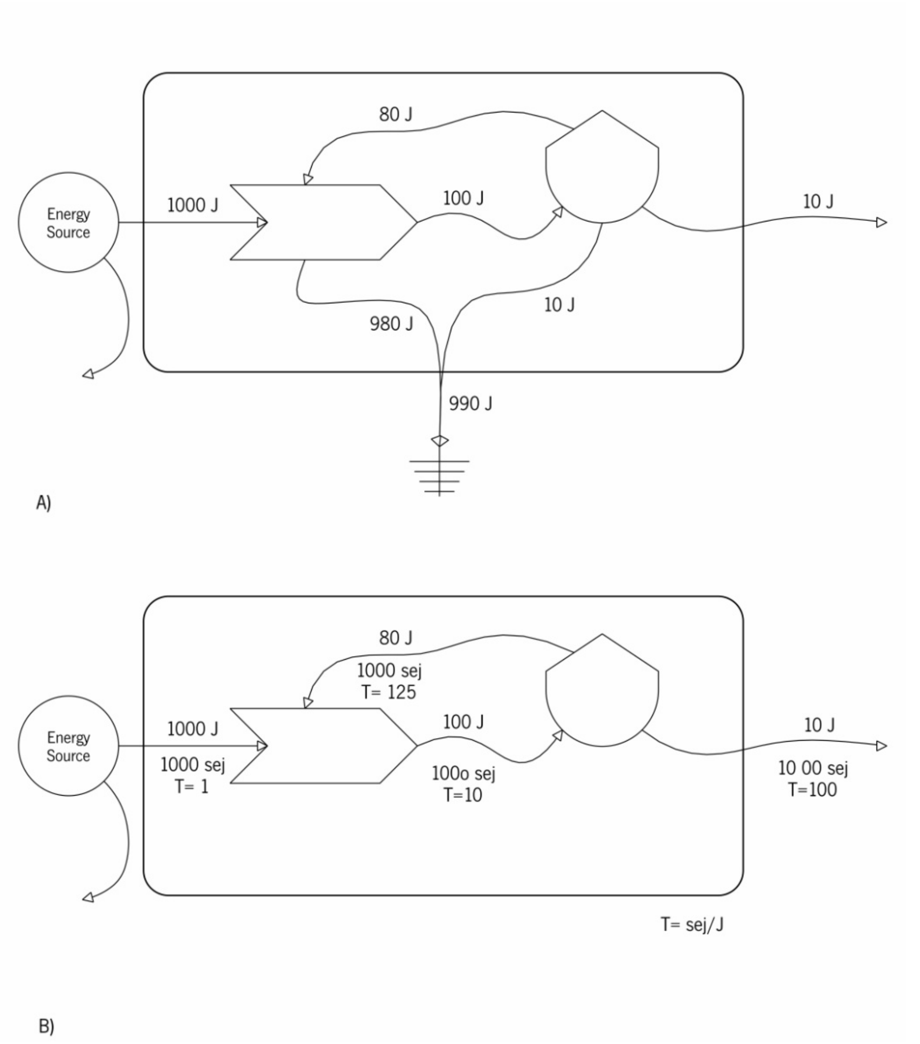


Figure 4.8. Calculation of Transformities: (a) Energy diagram according the First Law of Thermodynamics; (b) Emergy diagram with Emergy flows and Transformities (T) being calculated as T=Emergy/Energy.

A set of accounting procedures and rules must be followed to calculate Emergy within a system (Odum, 1996; Brown & Herendeen, 1996; Sciubba & Ulgiati, 2005), what is called ‘Emergy Algebra’:

(i) All source of Emergy to a process is assigned to the processes’ output (product);

(ii) By-products from a process have the total Emergy assigned to each pathway (by-products are considered as being those outputs that cannot be produced in a system without producing the other);

(iii) When a pathway splits, the Emergy is assigned to each "leg" of the split based on the percentage of the total energy flow on the pathway;

(iv) Emergy cannot be counted twice in a system: (a) Emergy in feedbacks cannot be counted twice; (b) by-products, when reunited, cannot be added to equal a sum greater than the source Emergy from which they were derived.

Other principle may also be considered (Sciubba & Ulgiati, 2005):

(v) Average Transformities are used whenever the exact origin of a resource or commodity is not known or when it is not calculated separately.

4.4 *Emergy and building construction*

Emergy Analysis has been widely applied in the evaluation of ecological systems, energy systems, and environmental impacts of processes and a large number of studies is available in the literature. Yet, despite such a wide debate, only a few studies have been produced concerning applications of Emergy Analysis to building construction and to building materials.

In most of these studies, Emergy analysis is employed as an environmental indicator for construction activities, building materials production and recycling (Buranakarn, 1998; Odum, 2002; Brown & Buranakarn, 2000, 2003; Huang & Hsu, 2003; Meillaud *et al.*, 2004; Pulselli *et al.*, 2007).

Odum (2002) presents a broad approach to the relationships of building construction with materials circulation and energy hierarchy. In the Emergy approach, buildings are a storage of materials that is the sum of the inputs during the construction process. This storage loses Emergy as building materials depreciate along time and become dispersed in the environment. New inputs by means of maintenance and repair actions keep the Emergy flow into the building system.

The necessary symbiosis between Earth processes and building construction in the use of the global cycle of materials is described by Odum (2002). Processes of providing materials to construction start with the slow work of our planet in concentrating stored reserves, such as mineral ores and rocks, and continue with human work in mining and processing those resources into stocks of construction materials and products. Materials and products incorporated in buildings are released again to the global cycle, after reaching their end of life.

Odum (2002) identifies three pathways for materials after reaching their end of life:

(i) Reuse of the highest quality components with some repair;
(ii) Reprocessing of remnants that are still concentrated;
(iii) Environmental recycle of the least concentrated waste materials, i.e. recycling to the natural processes capable of incorporating those materials again in natural storages.

An important assumption brought by Odum (2002) is that Emergy per mass is an indicator for the most beneficial recovering path. Materials with the highest Emergy per mass have more economic and environmental advantages for being reused and reprocessed, when compared with low concentrated materials that are more easily processed by global cycles.

Buranakarn (1998) and Brown & Burnakarn (2000, 2003) proposed a set of Emergy indexes to evaluate recycling patterns and recyclability of building materials. These Emergy indexes are suggested to measure the environmental benefits of three recycling trajectories: material recyle, by-product use, and adaptive reuse, i.e. recycling the material for a different purpose. The reuse option in the sense of reusing a product elsewhere was not considered in these studies.

Emergy per mass is also pointed as a good indicator for recyclability. Buranakarn (1998) and Brown & Burnakarn (2000, 2003) also recognizes that materials with higher Emergy per mass are more suitable for being recycled by human systems due to their ‘quality’, and have more environmental impacts when released to the environment.

in the context of an environmental approach, Huang & Hsu (2003) proposed a set of indicators based on Emergy to measure the effects of construction in Taipei’s sustainability: (a) intensity of resource consumption; (b) inflow/outflow ratio; (c) urban liveability; (d) efficiency of urban metabolism; and (e) Emergy evaluation of urban metabolism. The relevance of Emergy Analysis for that study was in the fact that it enabled the consideration of biophysical value of resources to the economic system. Evaluation of main Emergy flows of materials used due to urban construction provided both an understanding of their relative value and contribution to the ecological economic system (urban construction is equivalent to 44% of the Emergy used in Taipei), and a measure of the ecological interface of rapid urban development (environmental load of construction waste generation and recycling opportunities).

Meillaud *et al.* (2004) applied Emergy Analysis to evaluate an experimental building of three stories containing faculty and students' offices and a workshop, built in 1981, by including environmental, economical, and information flows. By including information flows generated by building occupants to the analysis of the whole building system, it was possible to calculate the outputs generated by the building usage: Emergy per educated student, Emergy per publications, Emergy per courses and Emergy per 'services'.

The significance of Emergy per unit values was highlighted by Meillaud *et al.* (2004), because there were few available Emergy per unit references for most commodities inputed into the building.

Aspects regarding the suitability of Emergy Analysis when compared with Embodied Energy Analysis, Exergy Analysis and Life Cycle Assessment (LCA) were also stressed by Meillaud *et al.* (2004):

(i) Concerning Embodied Energy and Emergy, results show similar kind of information: the higher the specific emergy and the embodied energy per mass, the more relevant its potential recycling;

(ii) Concerning Embodied Energy, Exergy analysis and LCA, these methods were not able to evaluate information or monetary flows and just account for the energy on the information carrier, i.e. computers, paper, and disks.

Another application of Emergy to building construction was published by Pulselli *et al.* (2007). The authors proposed a set of environmental indices to provide a basic approach to environmental impacts of buildings by accounting for the main energy and materials inflows within the building construction process, maintenance, and use:

(i) Building Emergy per volume (Em-building volume): this represent the 'environmental cost' of the building;

(ii) Building Emergy to money ratio (Em-building/money ratio): this represents the ratio of total Emergy used to money (seJ/€);

(iii) Building Emergy per person (Em-buildings per person): this represents the rate of Emergy use of human systems with relation to buildings.

The proposed indices based on Emergy accounting provide a framework for evaluating and comparing different building typologies, technologies and materials, regarding different manufacturing processes, maintenance, use, thermal efficiency and energy consumption.

Pulselli *et al.* (2007) argue that buildings are like full Emergy reservoirs (storage) that persists in time, and that Emergy analysis of a building highlights the durability of materials as a factor for sustainability.

With reference to building materials, the most extensive study on Emergy and building materials was developed by Burnakarn (1998) in order to identify recycling patterns. The author made calculations for several common materials. However, the values presented for metals and plastics do not include the final stage of transforming the raw material into building products, such as extrusion of aluminium for profiles production.

Other single reference values for building materials may be found dispersedly in literature, yet in general calculation procedures are omitted, thus hindering an analysis of their accuracy and data source.

4.5 *Recycling paths for building materials in Emergy Analysis*

To keep production systems running and economy growing, an available source of materials is needed (Ayres, 1998, 1999). As the demand of new materials is higher than the dispersion of concentrated materials by means of natural chemical, biological and geophysical processes, waste materials become a new source of available raw materials. The importance of waste materials to run the economy, in a planet with finite resources, was highlighted earlier in this Chapter.

This assertion is especially important for waste minimization and natural resources management. The availability of reusable waste materials is a core step to reduce depletion of non-renewable materials. This is also valid for a renewal material, i.e. the rate of replace-ability which does not meet the rate of demand, such as in high density wood harvesting that contributes for the destruction of rain forests.

In an Emergy context, Odum (2002) pointed out that building construction and material use is limited by the energy hierarchy and the so called global cycle of materials, recognizing three pathways for materials after depreciation according to their energy hierarchy:

(i) To reuse by means of repair and upgrade operations those materials and components with high quality (highest Emergy per mass);

(ii) To reprocess remnants materials that are still concentrated by feeding back production systems;

(iii) To dispose the least concentrated waste materials in such a way that natural Earth processes may recycle them and benefits ecosystems by reincorporating those materials in natural storages (lowest Emergy per mass).

Within such approach, Emergy per mass would indicate the appropriate path for materials recovery in a way that benefits the overall system.

This principle is also pointed by Buranakarn (1998) and Brown & Buranakarn (2000, 2003) by stating that Emergy per mass is a good indicator of recyclability, where materials with higher Emergy are more recyclable. Reuse or reprocessing of highly concentrated materials usually require less energy inputs when compared with processing the same material from virgin resources and thus reducing the environmental impacts resulting from discarding in landfills. The authors applied the concept of Recycle Benefit Ratio (RBR), which is the ratio of the Emergy used in providing a material from raw resource to the emergy used in recycling the material, to evaluate the relationship between recyclability and Emergy per mass.

Brown & Buranakarn (2000) in a similar study also included another recyclability ratio as a way to measure efficiency in recycling trajectories: the Recycle Efficiency Ratio (RER). RER is defined as the ratio of Emergy costs of recycling the Emergy of a material product from the raw resource that was not used because the recycled material substituted it. RER compares the Emergy used in a recycle pathway to the Emergy saved by substituting a recycled material for a raw product. RER also indicates the benefits of recycling high quality materials when compared with lower quality materials.

Both RBR and RER ratios present the same kind of results for recycled materials (see Table 4.3). The highest the ratios obtained, the higher is the recyclability and the recycling efficiency.

A comparison of recyclability of materials using RBR and RER ratios highlights the following aspects:

(i) Materials with high Emergy per mass are more adapted to recycling (e.g. aluminium and steel);

(ii) Downgrading recycling processes show to be less efficient even for materials with high Emergy per mass, such as recycling of plastics for recycled lumber production.

Table 4.3. Recyclability of selected common building materials in accordance with Brown & Buranakarn (2000, 2003).

Material	Emergy per mass (1) (seJ/g)	Recycled material	RER (2)	RBR (3)
Wood lumber	0.88 E+09	Recycled lumber	0.4	0.4
Concrete	1.54 E+09	Concrete with recycled aggregates	5.2	4.9
Glass	2.16 E+09	Ceramic tile from recycled glass	3.3	3.5
Steel	4.13 E+09	Recycled steel	15.5	14.6
Plastic (PVC)	5.85 E+09	Plastic lumber	3.3	2.9
Aluminium	12.53 E+09	Recycled aluminium	43.8	38.3

Notes:

(1) Emergy per mass according to baseline of 9.44 E+24 seJ/yr

(2) Source: Brown & Buranakarn (2000)

(3) Source: Brown & Buranakarn (2003)

RER: Recycle Efficiency Ratio

RBR: Recycle Benefit Ratio

Beyond the authors’ conclusions, it is also possible to conclude from these studies that benefits of recyclability of materials are not just related with Emergy per mass, but also related with the process by which such materials are returned to the production system, i.e. reuse of the product, recycling the material with upgrading, recycling the material for the same purpose, recycling the material with downgrading, and recovery of the energy content of the material (heat).

Furthermore, in accordance with Brown & Buranakarn (2003) quality and versatility of a material may be related to its Emergy per mass. The larger the Emergy per mass the more valuable and versatile the product. Materials such as aluminium have a wide range of high performance applications, when compared with wood or cement. Such statement is in accordance with the principles of the hierarchical cycle of materials concentration.

The Emergy of a recycled raw material is the sum of the Emergy of the raw material substituted (including refining) plus the Emergy inputs for collecting and refining the recovered material. The Emergy of a recycled product is the sum of the raw material substituted, plus the inputs for collecting and refining the recovered material, plus the Emergy inputs for transformation and use.

A recycling system and Emergy accounting principles for recycling pathways is proposed by Brown & Buranakarn (2003) (see Figure 4.9).

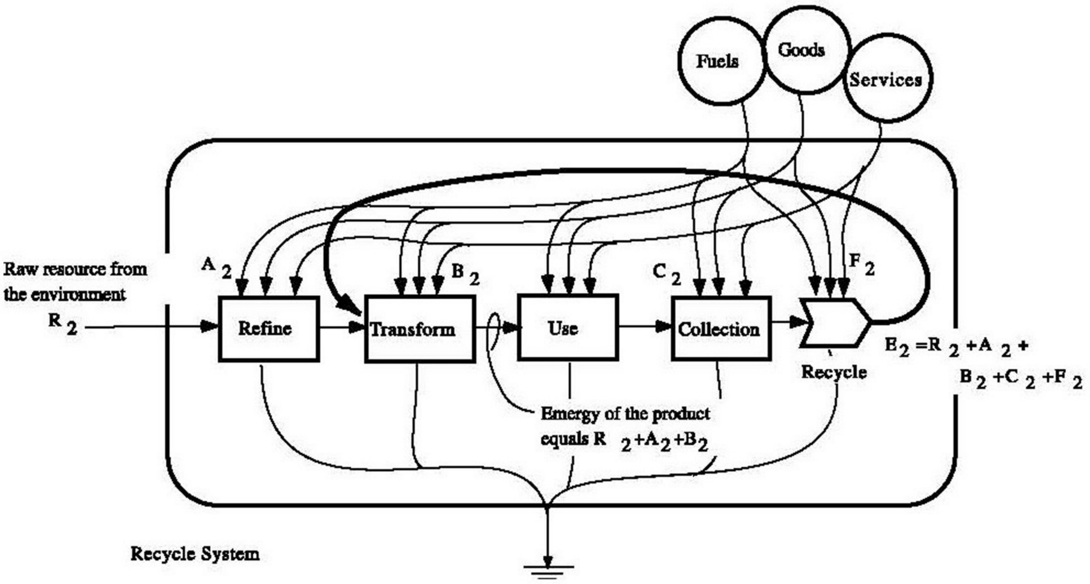


Figure 4.9. Aggregated recycling system according to Brown & Buranakarn (2003).

The Specific Emergy input of recovered materials must equal the Specific Emergy of the substituted raw material plus the Emergy of recovering it as a raw material. This procedure avoids doubling accounting the Emergy inputs of transforming and processing the initial product that was later recovered. This principle is in accordance with Buranakarn (1998) procedures for the Emergy accounting of recycled materials.

4.6 *Discussion*

Two main aspects may be pointed out to understand the suitability of the Emergy theory for the aim of this study. The first issue is related with the kind of conclusions that it is possible to acquire from applying the Emergy Analysis to a net benefit analysis of materials recovery. The second issue concerns the limitations and accuracy of the Energy Analysis procedures, regarding the available information at present. Both issues are here discussed.

4.6.1 *Emergy Analysis and environmental load of materials*

Emergy theory is a systems analysis tool that includes flows of energy, materials, money and information in a same common unit. By accounting for quality difference among distinct forms of energy and materials, Emergy expresses the environmental value of energy and materials, and the contribution of the biosphere for all systems. That aspect is relevant to understand the net benefit of materials recovery and resources management.

To accomplish with the aim of this study, Embodied Energy Analysis presents several constraints to express both the nature and human work that is necessary to produce a commodity. Further, available Embodied Energy values do not distinguish the quality of energy that has been used, by expressing all energy flows in the same heat measure (J or cal). Normally, Embodied Energy seems to not consider differences between renewable and non-renewable sources of energy. Values found in literature omit such information. For example: electricity produced from fossil fuels does not have the same impact as electricity produced from wind or from hydraulic.

By distinguishing a quality hierarchy in energy and materials, Emergy enhances their capacity of producing work. The more the convergence of a material the higher is its quality. Quality is understood as being a measure of its concentration and environmental value, and not a measure of its physical condition.

This property is also a measure of its environmental impact if dispersed in nature. High quality materials are only recyclable by nature through dispersion processes at the long run such as heavy metals or volatile organic compounds (VOC). On the contrary, low quality materials, such as wood, are easily dispersed in nature by actions of energy and chemical processes.

Recyclability ratios presented by Buranakarn (1998) and Brown & Buranakarn (2000, 2003), show that Emergy per mass is a good indicator for the recycling benefits of materials recovery.

In accordance with the energy hierarchy and materials convergence, Emergy highlights the influence of end-of-life scenarios for the environmental benefits of closing the materials loop.

4.6.2 *Emergy per mass calculations*

Uncertainties in Emergy analysis seems to be related with the accuracy of Emergy per unit values. The use of average values or values derived from several different studies has been a solution to fill the lack in available information, since Emergy per unit calculations are time consuming and need good sources of information such as Life Cycle Inventories.

However, Emergy per unit values may differ according to space and time, and mainly to the accuracy level of such calculations. For example, several materials and sources of energy may range quite different Emergy per unit values (see Table 4.4).

Table 4.4. Comparison between several sources for Emergy per unit values for selected building materials and products (values are presented according with base line of 15,83).

Item	seJ/g	seJ/g	seJ/g
Aluminium ingots (primary)	1.97 E+10 (1)	4.58 E+10 (3)	
Portland cement	3.33 E+09 (1)	3.53 E+09 (2)	5.54 E+10 (3)
Concrete	2.42 E+09 (1)	3.40 E+09 (2)	6.75 E+09 (3)
Limestone	1.68 E+09 (4)	9.50 E+09 (5)	
Rock wool	2.52 E+08 (6)	3.09 E+09 (7)	

Sources:

(1) Buranakarn (1998), (2) This study, (3) Wang *et al.* (2006), (4) Odum (1996), (5) Odum (2000), (6) Ulgiati & Brown (2002), (7) Bjorklund *et al.* (2001)

As observed in Table 4.4, assumptions made for Emergy per unit in Emergy accounting may be misleading and produce inaccurate results. However, Meillaud *et al.* (2004) states that errors arising from use of average Emergy per unit stand usually in an acceptable range and even changing the numerical results would not change their tendencies. To minimize this constraint, the origin and the context of those studies must be taken into account when choosing between different values.

Human labour and services inputs seem not to influence significantly the Emergy per unit results, both for materials and building construction. Buranakarn (1998) showed that there are not significant differences in Emergy per unit with and without services for a wide range of selected building materials (see Table 4.5). A comparison between selected building materials shows that differences range from around 1% to 15%.

Table 4.5. Comparison between several Emergy per unit values with and without services for selected building materials and products presented by Buranakarn (1998) (values are presented according with base line of 15,83).

Item	Without services	With services	Variation
Aluminium ingots	1.91 E+10	1.96 E+10	0.026
Brick	3.67 E+09	3.72 E+09	0.013
Cement	3.67 E+09	3.69 E+09	0.005
Ceramic tile	4.80 E+09	5.14 E+09	0.070
Lumbers	1.39 E+09	1.47 E+09	0.057
Plastic lumber	8.46 E+09	9.66 E+09	0.141
Plywood	1.81 E+09	2.03 E+09	0.121

At the building level, Pulselli *et al.* (2007) calculated the human work as being 2% of the total Emergy used in the building construction. Meillaud *et al.* (2004) does not even account for human work in the Emergy evaluation of the building.

4.6.3 *Final remarks*

Specific Emergy is considered an adequate measure of materials recyclability: the higher Specific Emergy (high quality materials) the more recyclable is the material (Buranakarn, 1998; Odum , 2002; Brown & Buranakarn, 2000, 2003; Meillaud *et al.*,2004).

Emergy Analysis does not provide the same data as the most common tools for environmental assessment of buildings, such as the SBTool, the Leadership in Energy and Environmental Design (LEED), or the Building Research Environmental Assessment Method (BREEAM). These methods provide the so called state-pressure environmental indicators, by analysing specific parameter through conventional physical units in order to verify their level of accordance with the established environmental benchmarks.

In spite of the limitations and problems that were pointed out, Emergy Analysis proves to be an integrative methodology and thus it is able to produce environmental indicators in accordance with its principles. By evaluating both natural and human investments in production systems (convergence) and their role in waste metabolism (dispersion), the estimation of the net benefit of materials recovery is enhanced.

CHAPTER 5

PROPOSAL OF A MODEL TO EVALUATE MATERIALS RECOVERY EFFECTIVENESS

5.1 *Introduction*

Whether the resources consumption in building construction will be reduced or not in the future, recovery is dependent on the implementation of a supply-loop chain. However, the economic and environmental feasibility of such a supply chain is also dependent on the availability of materials and components to be recovered.

To keep the supply-loop chain running, it is necessary to assure the required amount of recoverable materials in order to reduce the dependence on virgin raw materials. Yet, availability of recovered materials for reuse and recycling is a difficult question to be answered, because it is dependent on the number of buildings that will be dismantled in the future, and on the technical quality of the salvages. The properties of the recovered products will determine if they will be discarded or if they will be kept in the production chain, and in that case which is the feasible path for reprocess.

Therefore, both economic and environmental feasibility of materials and components reclaim are related with the amount and the quality of the reclaimed materials and components. It seems reasonable to assume that these two aspects are the result of the disassembly level of the buildings or building elements. Existing buildings and most of the current buildings exhibit low levels of disassemblability, which increase dismantling, collection and separation costs regarding the salvaged materials, decrease their technical quality, and limit technical reprocessing options, which causes were discussed earlier in Chapter 2.

From such assessment, became clear that the lack of an Extended Producer Responsibility applied to construction products, i.e. buildings, and in spite of a general increase in the amount of recovered construction and demolition waste, materials reprocessing will generally be kept at a downcycling level. In such a scenario, opportunities for Design for Disassembly have to be recognized as a crucial element to feed the supply-loop chain, and to improve the quality of salvaged materials and components. Lessons from other industries, such as electronics and automotive, may help on driving the changes on current practices.

However, it seems clear that for such an approach, a set of questions should be highlighted:

(i) Probably, most of the new buildings will be built using cement and concrete, and ceramic materials as the main technological options, due to their reduced economical costs, durability, and availability;

(ii) Maintenance, repair, and adaptive use of spaces are changing the traditional technological systems, by replacing in fit traditional building systems, such as internal masonry walls, for more flexible and integrative systems;

(iii) Design for Disassembly will be performed at different hierarchical levels regarding the expected lifespan and the functional flexibility, with priority for the layers with shorter useful life, such as internal partition, infrastructures, and finishing;

(iv) The economic value of salvage materials will be a function of their quality and will sustain a supply market based on collection and reprocessing of end-of-life materials and components;

(v) The environmental value of salvage materials will be a function of the virgin resources saved by using those recycled.

With these aspects as background and in order to evaluate building disassembly at the design stage it is necessary to take into account the amount and quality of the recoverable materials, and the environmental benefits of such recovery. Per se, the application of building disassemblability measuring tool does not express the environmental net benefits of materials and components recovery.

Therefore, the evaluation of building deconstruction and of the patterns of recovered materials in order to measure its real environmental benefits and value, becomes an important goal to be achieved. Environmental benefits and the value of building deconstruction practices are not just inherent to the amount of recovered materials, but also inherent to the raw materials that are saved and kept as natural resources. Thus, assessment tools integrating environmental parameters will be more realistic on measuring the environmental effectiveness of buildings disassembly, and ultimately of the materials and components recovery.

Earth is the main recycler. Earth recycling processes happen at various scales and states of matter, from the small scale of nutrients to the biggest scale of minerals. Different materials have different natural recycling paths and timescales, notably the difference between organic and inorganic matter. Thus, the importance of a recovered material is not just a question of non renewal resources management, but it is also related to the hidden value of global earth systems work in providing such resources.

Materials have different environmental loads, both for natural and industrial processing. In general, earth global processes are kept out of the equation and evaluation systems that tend to focus mainly on industrial production systems and evaluation of end-of-life scenarios. For example, life cycle approaches do not include the work of nature as part of a material's cycle. Such a broad perspective would recognize the Earth as the main regulatory system.

5.2 *Proposal of the Model: theoretical approach*

The idea of 'Effectiveness' is the key concept brought in this Model. Effectiveness goes beyond efficiency, as it is an expression of quality rather than just an expression of quantity, like materials recovery ratios or embodied energy analysis. Effectiveness measures a net benefit for the society and the environment, and thus allows estimating the value of natural resources that are saved by building materials recovery.

To measure Effectiveness, Emergy accounting is applied. As described in Chapter 4, by placing materials production in a hierarchical chain of materials concentration, Emergy evaluates the enhancement of their quality and versatility. Furthermore, by including earth global processes in the system analysis, Emergy accounting highlights both nature and human investments by using a common unit, the Solar Emjoule (seJ).

Being a measure of the available energy and matter already used up Emergy is a property of the amount of matter and energy in the transformed product. Being an intrinsic property of energy and materials Emergy allows comparing different processes and products, which in other way would not be easily comparable.

Furthermore, buildings are non-steady systems that are in permanent change:

(i) A building is a system acting according to Thermodynamic laws, where materials and components tends to equilibrium with their environment through chemical and physical processes of natural degradation;

(ii) New materials are added to the building during its Lifespan due to degradation and outdating, by means of repair, maintenance, and upgrade operations in order to meet the technical and the users requirements;

(iii) Building requirements evolves in time due to obsolescence, which may occur by changes in legal standards, user needs, aesthetic references, or spatial adaptation;

(iv) Buildings may change by means of adaptive reuse in order to meet new requirements of function and dimensions.

The changing processes that occur in buildings create an inconstant flow of materials and components during their Lifespan, in order to keep a given set of requirements fulfilled, be they mechanical, technical, legal or aesthetic.

In Figure 5.1, showing the Emergy diagram of a building evidences the generic flows within a building system. In this diagram, a building is not just a product, but also a storage of materials and components, that were brought together by means of construction activities (production) and maintenance and repair activities (usage). As in any storage, materials and components within a building keep flowing due to natural degradation and to obsolescence, thus originating degraded or obsolete materials that will flow outside the system.

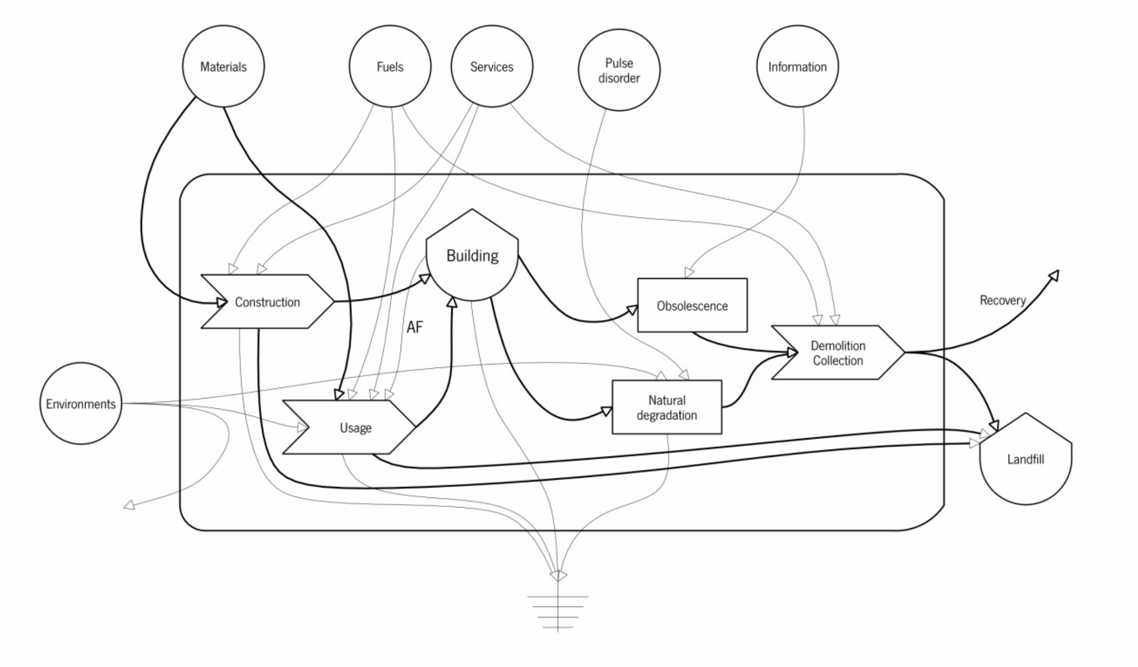


Figure 5.1. Emergy diagram of the life cycle of a building (materials flow highlighted).

Environmental actions, as materials tend to thermodynamic equilibrium, are in the origin of natural degradation processes. Sometimes, a pulse disorder may lead to partial or overall degradation of the building, such as a hurricane, an earthquake or a fire. However, obsolescence is driven by information that will either keep or change the requirements that are expected to be fulfilled. As a result, new materials keep being added, in order to replace or to upgrade the degraded or obsolete materials and components.

Finally, degraded materials and components are collected by demolishing or deconstruction activities, and will flow outside of the system to be recovered (i.e. reused or recycled) or to be disposed.

Having in mind, that Emergy per mass of material is an expression of its environmental load, and of its recycling potential, the environmental net benefits may be assessed by comparison with natural resources that are saved by reclaimed materials.

Therefore, the benefits of building disassembly would be expressed as the net environmental benefit ratio between the Emergy of raw materials, which are saved by recovering building materials, and the total Emergy inputs in the building or building element. Such index describes the Deconstruction Effectiveness (DE) of a building or building element, as a function of the benefits to natural resources conservation.

Such an approach is in accordance with the Emergy principles early described in Chapter 3, especially with the principles for Emergy recycling calculations.

5.2.1 *Allocation of data*

The Deconstruction Effectiveness index is a condition of the available information regarding the object under analysis. Such information describes the building or building element regarding a set of information parameters that need to be considered for calculations.

As effectiveness is related on the environmental value of the materials and the application of Design for Disassembly principles, the required information parameters are obtained by analyzing the constraints to building disassemblability and the most feasible end-of-life scenarios under such conditions.

Therefore, a set of data must be allocated to the Model in order to estimate the Emergy flows to be assigned to the system. Such data includes information on materials and components properties (e.g, density, Emergy per mass, forecast service life, recovery paths, recovery rates), and information on building configuration to obtain variable data, such as embodied mass flow, building lifespan, useful life of materials and components, types of connections, assembly sequences , feasible end-of-life scenarios, and substituted materials.

5.2.2 *Emergy flows considered for allocation*

The allocation of the Emergy flows is based on the principle that when a material reaches its end-of-life it is replaced by the same material. The statement of this principle is grounded on the following aspects (see Figure 5.2):

(i) The building needs a constant flow of materials to keep its functionality;

(ii) Once it is not possible to predict the functional and spatial changes that may occur in the building and in materials and components, it is assumed that the initial requirements and materials input will be kept the same during the building lifespan, as if it was kept in a functional and architectural 'steady-state';

(iii) Since several materials are replaced during the lifespan of the building, such replacements must also be allocated to the total Emergy of materials inputs into the building.

As the proposed Deconstruction Effectiveness (DE) index is the environmental net benefit of materials and components recovery, only the Emergy flows of building materials are allocated to the proposed Model. The DE index does not compare the Emergy intensity life cycle of recycled materials with the Emergy intensity life cycle of non recycled materials. Life cycle Emergy intensity measures the total Emergy used for materials from cradle to grave, by including materials, construction, demolition, collection, sorting, and landfilling.

By including the Emergy of construction activities in the DE index calculations, the total Emergy obtained would be the Emergy of the building and not only the Emergy of the materials. For materials comparison, Emergy of construction, demolition, and collection should not be included, because when a material is recoverd, its functional performance is lost because it is a condition of the building and not of the material itself.

In fact, for Emergy calculations for recycled materials, previous Emergy for construction is not included to avoid double counting when the recycled material is relocated into a new building.

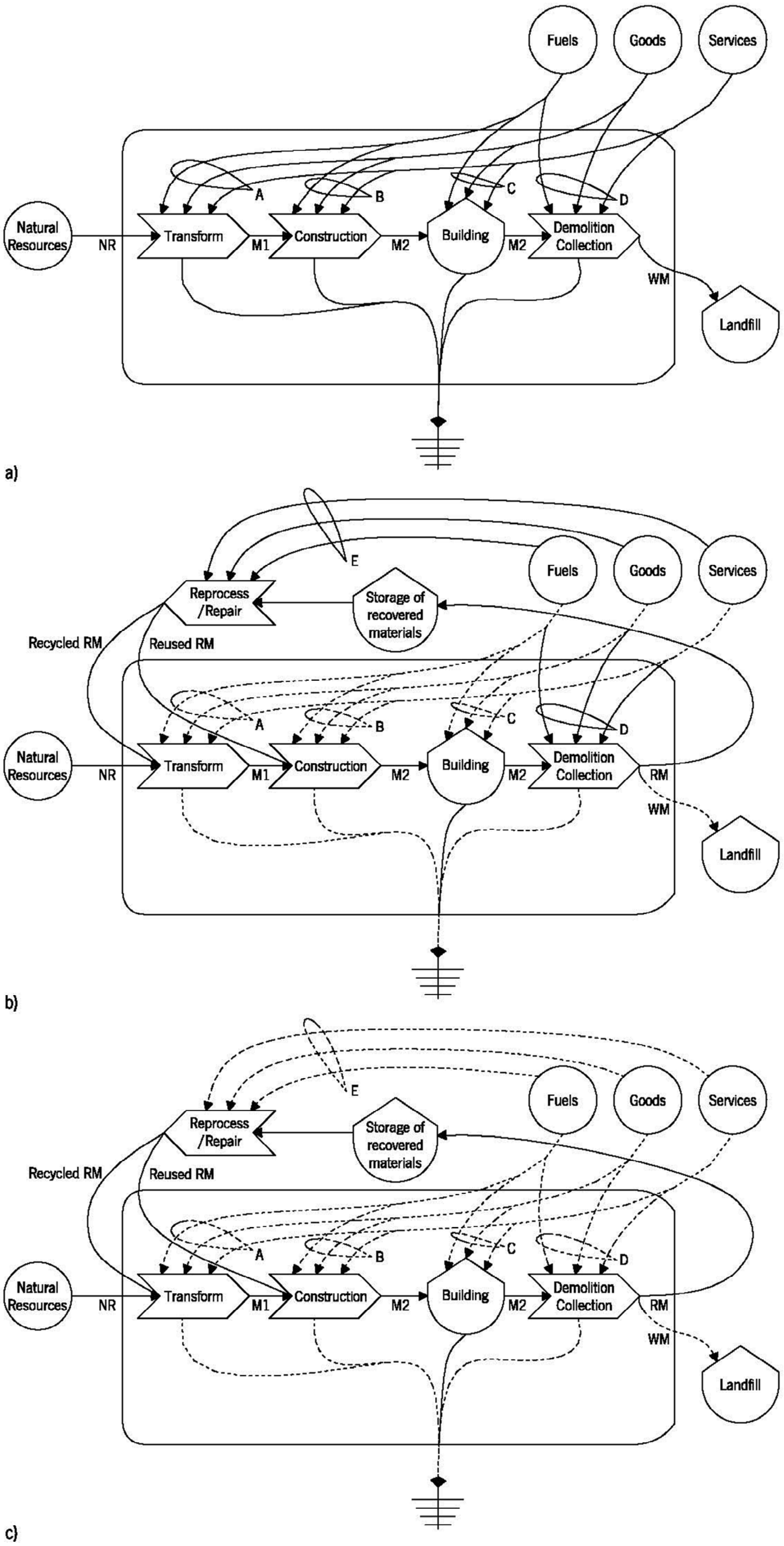


Figure 5.2. Emergy allocation: (a) Life Cycle Emergy intensity: all flows are allocated; (b) Emergy of recycled materials: only D, E, and RM are accounted and RM equals the Emergy of the NR that were saved; (c) Deconstruction Effectiveness index: only M1 and RM are accounted and RM equals RN for recyclable materials and M1 for reusable materials and components.

5.3 *Goal and aim of the Model*

In this context, a Model to evaluate the effectiveness of building materials recovery was developed, throughout the assessment of the building system in order to establish a Recovery Effectiveness index according to the building Life Span. This index evaluates the environmental net benefit of materials recovery, by relating the amount and quality of salvaged materials, end-of-life scenarios, and the natural resources and new products that would be saved by closing the materials loop.

This index would translate the qualitative relationship between salvaged materials and saved natural resources.

However, it is not a goal of the proposed Model to evaluate the environmental load of a single material or component or the environmental load of reuse and recycling processes. Environmental impacts of materials are described by using Life Cycle Assessment tools.

In addition, is not a goal of the proposed Model to evaluate Disassembly planning sequences in order to improve disassembly tasks and decrease disassembly costs.

The proposed Model does not intend to describe the disassembly leveling of the building or building element, because such description is not a condition of the environmental net benefit of materials and components recovery.

However, the proposed Model employs life cycle and Design for Disassembly principles in the evaluation procedures, in order to describe materials and components properties, and to describe the building configuration and physical constraints to disassembly.

Being a qualitative index, to describe quality aspects of materials and components recovery within the Model, a qualitative approach as the Emergy method is applied, rather than a quantitative method such as Embodied Energy method.

The proposed Model has its major application at the design phase, by evaluating materials options and building systems configuration and hierarchy, comparing different solutions and options, and ultimately supporting decision-making. The users of the proposed Model are researchers and building designers

In addition, the proposed Model may be applied both to whole building systems and to single building elements.

5.4 *Framework of the proposed Model*

A set of procedure levels composes the framework of the proposed Model, which encompasses information collection and analysis, calculation and feedback steps regarding a building or building element (see Figure 5.3). These procedures are the following:

(i) Step 1: Development and update of a database (information level);

(ii) Step 2: Analysis of the architectural and technological configuration (information level);

(iii) Step 3: Deconstruction Effectiveness index (calculations level);

(iv) Step 4: Improvement of the overall solution (feedback level).

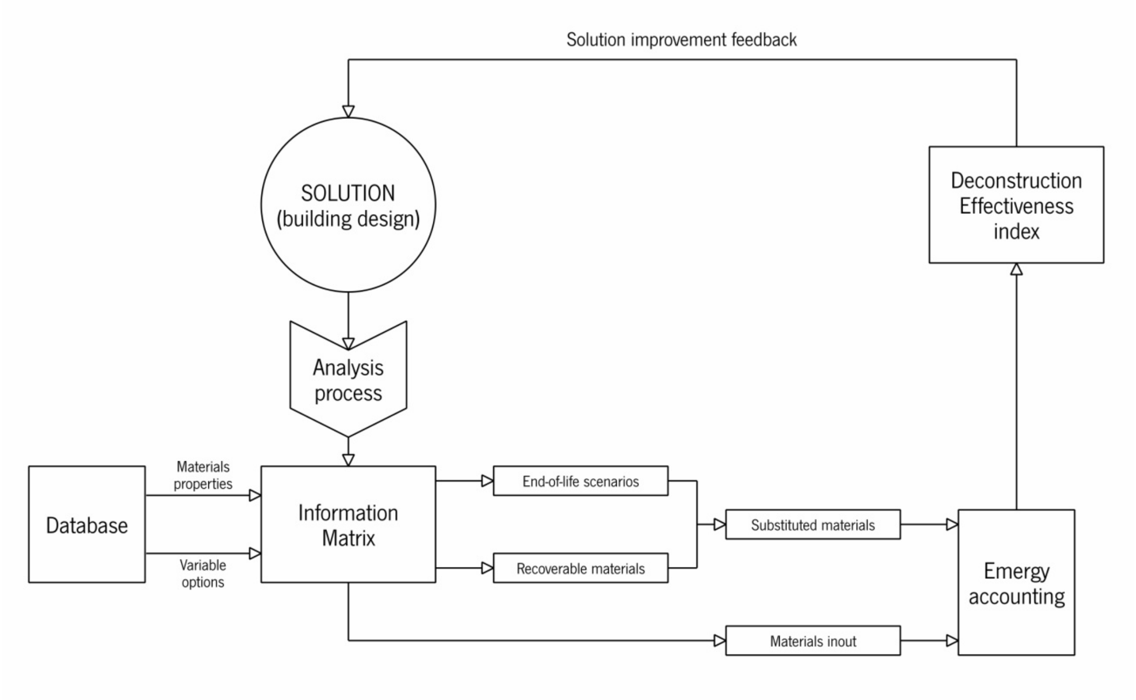


Figure 5.3. Framework of the proposed Model.

Grounded on a system analysis approach, the two first steps of the proposed Model are based on information inputs and information analysis that will be needed to perform the third level, i.e. the calculations of the Deconstruction Effectiveness. These information inputs are of two kinds and have two different sources:

(i) Constant values (database);

(ii) Variable values (user options).

In the first step, the set of values to be collected refers to materials properties, which are stored in a database, and is common to all different analysis.

In the second step, the building configuration is analysed in order to collect information that is expected to influence the Deconstruction Effectiveness index, such as Useful Lives, connections employed, recovery scenarios, and best options on substituted materials, and these data are used as inputs.

In the third step of the proposed Model framework, the DE index is calculated by means of a set of equations. These equations are based on the Emergy accounting procedures.

The fourth and final step is optional for the user. The feedback information allows to selectively improve the overall solution, by making changes on the initial inputs to achieve a better DE index. These changes might be made under several parameters, such as materials choice, hierarchy, connections types, and end-of-life Scenarios.

Due to variable information input and users decision-making, the proposed Model has a dynamic framework, which allows the analysis of several options in order to get the best possible environmental performance regarding the effectiveness of salvaging building materials, and the identified constraints, such as market demands, technological feasibility, and solution costs.

5.4.1 *The Model's database*

The data to be allocated to materials are organized in a material properties database. Such database stores the information regarding the Model constants for the building materials and components. These constant values are intrinsic properties of materials and components.

These data do not change due to design decisions such as connection types and hierarchy between materials or components, and do not change due to design decisions on building technological systems (e.g. structure, façades, and walls).

These data include the following issues:

(i) Density;
(ii) Service Life;
(iii) Recovery paths;
(iv) Recovery Rates;
(v) Specific Emergy values.

Despite being about properties of materials and components, the information stored in the database may be upgraded as long as new or more accurate information becomes available, such as progresses in materials and components composition, durability, manufacturing processes, and recycling processes. Thus, the material properties database may become a dynamic set of information.

(1) Density

In the proposed Model, values for embodied Mass of materials and components are needed to calculate the overall Emergy flows crossing the system boundaries. The Mass of a specific material will be according its density and the quantity input.

Density values might be established by:

(i) Standards (e.g. concrete, mortars, bricks, glass);
(ii) Research (e.g. rocks, wood, minerals);
(iii) Manufacturers (e.g. composite materials).

Often standard and research density values may present minimum and maximum values for a material. In such cases, for the proposed Model, the density reference for Mass account is considered as the mean value.

For similar materials, manufacturers may present different density properties. The accuracy of these data may be improved by using specific data of the manufacturer instead of generic data for each case. In such cases, information from the manufacturers may be added into the proposed Model database.

In order to estimate embodied Mass, density values of reference for materials and components considered in this study are presented in Appendix B.

(2) Forecast Service Life

Forecast Service Life is defined in this study as the predicted period of time during which the performance of a material or component will meet the performance requirements.

Since the proposed Model is expected to be applied at the design stage, Service Life of materials and components becomes unknown because SL is a function of environmental conditions, in usage conditions, and outdate constraints. Thus, Forecast Service Life values for materials and components were considered as reference values. As defined in standard "ISO 15686-1:2000 Buildings and Construction Assets, Service Life Planning Part 1: General Principles presents definitions and the framework for a methodology on Service Life estimation", Forecast Service Life values are obtained from both estimation and recording methods.

Due to their different durability, materials will either need to be, or not, replaced during the Lifespan of a building or a building element. Thus, to account for the overall amount of materials that will keep the building meet the operational requirements, all inputs of materials during its Lifespan are to be considered.

The Model will behave itself dynamically by accounting the Emergy flow of materials during the Lifespan of the building or building element under assessment. This condition allows the analysis of material inputs as flows in a storage, i.e. building or building element, instead of accounting them just as an initial input.

However, not being possible to anticipate the changes that may occur in the future, such as spatial requirements, new materials, and upgrade to infrastructures, the initial design solution will act as the reference requirements for the Lifespan of the building or building element assessed.

As general conditions input for data on Forecast Service Life, were considered:

(i) If the Forecast Service Life does not exceed the Lifespan of the building or building element, the initial input plus the number of necessary replacements of materials or components to keep the system running will be accounted; for example, a material with a service life of 20 years will be accounted 3 times for a building with a Lifespan of 50 years.

(ii) If Forecast Service Life of a material or component exceeds the Lifespan of the building or building element, its reuse will be considered as possible or feasible, depending on salvaged conditions;

(iii) If Forecast Service Life of a material or component does not exceed the Lifespan of the building or building element, its recycling or disposal will be considered as possible End-of-life Scenarios, depending on salvaged conditions.

Collected data and values on Forecast Service Life were obtained from literature and are described in Chapter 3. The reference values to be considered in the proposed Model's database are presented in Table 5.1 and were established in accordance with the following parameters:

(i) Most common building materials and components;

(ii) Longer Forecast Service Life for those with different Service Life.

Table 5.1. Forecast Service Life for selected building materials and components to be considered in the Model's database (see Chapter 3 for references).

Material	Component/service	Forecast Service life (years)
Aluminium	Door and window frames	30
	Siding	80
	Roofing	35
Asphalt	Roofing shingles	20
Asphalt (Hot-mix)	Pavement (parking)	50
Cement	Mortar	60
	Stucco external finishes	100
	Fibre cement shingles	45
	Concrete paving	30
Ceramic	Ceramic tiles (walls)	30
	Ceramic tiles (flooring)	50
	Sanitarian	20
Clay	Brick masonry	100
	Facing bricks	100
	Roofing tiles	100
Concrete	Structural elements	100
Copper	Roofing	40
	Pipes	50
Cork	Flooring	50
Glass	Flat glass	60
	Fibreglass	50
Gypsum	Plasterboard	75
	Traditional interior plaster	50
Lime	Plaster	60
Paints	Plaster and mortar finishing	15
Plastics : HDPE	Pipes	30
	Plastic lumber	50
Plastics : Melamine-formaldehyde	Laminate surfaces	10
Plastics : Nylon	Carpet	15
Plastics : Polyamide (PA)	Carpets	10

Table 5.1. Continued.

Material	Component/service	Forecast Service life (years)
Plastics : Polystyrene (PU)	Cladding out insulation (including finishing)	50
Plastics : Polyurethane (PU)	Foam insulation	10
	Roof spraying	20
Plastics : PVC	Window frame	25
	Flooring	35
	Wall covering	10
	Roofing sheets	120
Rock (natural)	Flooring tiles	100
	'Terrazo' flooring	50
	Mineral wool	50
	Slate roofing tiles	50
Steel (galvanized)	Roof claddings	45
	Wall claddings	60
	Pipes	50
Steel sections (Galvanized)	Exterior wall framing	75
	Walls and floors	200
	Exterior doors	30
Wood	Columns and beams	150
	Wood frame	150
	Exterior windows and doors	40
	Platforms and posts	35
	Solid wood flooring	30
	Linoleum (mostly wood flower)	30
	Wood plank (interior)	50
	Plywood	15
	Oriented Strand board (OSB)	85
Wood coatings	Paint (external)	10
	Varnish (windows external finishes)	<3
	Varnish (external finishes)	<3
Wool	Carpet	25

(3) Recovery patterns

Recovery patterns are properties of materials or components, and are defined as the possible or feasible options by which they might be recovered in order to close their life cycle loop.

The quality conditions that salvaged materials present is a condition for evaluation of different options for recovery, both for reuse and recycling End-of-life Scenarios.

For the proposed Model, principles for the definition of the recovery patterns for a material or component are the following:

(i) Best End-of-life Scenario option;

(ii) Best option for the conditions in which the material or component might be salvaged.

As best option, it would be considered the most feasible technique or process that would maximize the reuse or recycling of a material or component.

However, it must also be considered that it is possible to assign several recovery patterns to a material or component according to the recovery rates established in the proposed Model and to the kind of connections used. As an example, for a demountable wood structure it would be possible to considerer a partial recovery for structural purposes in a Reuse scenario, and a partial recovery of the wood that would not be possible to reuse as wood chips for plywood production in a recycling scenario.

Collected data and references on feasible recovery patterns for materials and components are described in Chapter 3. Optimal options for selected building materials recovery are here summarized, considering reuse, recycling, and incineration as end-of-life scenarios.

Recovery patterns for C&DW are summarized in Table 5.2 according to the references indicated in Chapter 3 (see 3.2.1).

Table 5.2. Recovery scenarios for C&DW.

Material	Component/Service	End-of-life scenarios		
		Reuse	Recycling	Incineration
Stony rubble	Concrete and masonry	- Not suitable	- Coarse fraction as aggregates for new concrete and mortars - Fine fraction as aggregates mortars; - Aggregates for road layers	- Not suitable
Clay	Bricks masonry and tiles	- Not suitable	- Aggregates for new clay bricks - Sand replacement in concrete	- Not suitable
Concrete	Structural elements and blocks masonry	- Not suitable	- Aggregates for new concrete and mortars - Aggregates for road layers	- Not suitable
Porcelain	Sanitary installations	- Suitable	- Coarse fraction of aggregates in concrete	- Not suitable
Gypsum	Plaster	- Not suitable	- Not suitable	- Not suitable

Recovery patterns for concrete are summarized in Table 5.2 according to the references indicated in Chapter 3 see (3.2.2).

Table 5.3. Recovery scenarios for concrete.

Material	Component/Service	End-of-life scenarios		
		Reuse	Recycling	Incineration
Concrete	Precast structural elements	- New structural frames	- Coarse and fine aggregates for new concrete and mortars - Aggregates for road layers	- Not suitable
	Cast-in-place	- Difficultly suitable		

Recovery patterns for blocks, bricks, and tiles are summarized in 0 according to the references indicated in Chapter 3 (see 3.2.3).

Table 5.4. Recovery scenarios for blocks, bricks, and tiles.

Material	Component/Service	End-of-life scenarios		
		Reuse	Recycling	Incineration
Concrete	Blocks	- Suitable (depending on masonry mortar)	- Aggregates for new concrete and mortars - Aggregates for road layers	- Not suitable
Clay	Bricks	- Suitable (depending on masonry mortar)	- Gravel and sand substitute for new concrete and mortars	
	Tiles	- Suitable (depending on materials quality)	- Aggregates for road layers - Aggregates for clay products	- Not suitable

Recovery patterns for stone are summarized in Table 5.5 according to the references indicated in Chapter 3 (see 3.2.4).

Table 5.5. Recovery scenarios for stone.

Material	Component/Service	End-of-life scenarios		
		Reuse	Recycling	Incineration
Stone	Masonry	- Suitable (depending on masonry mortar)	- Aggregates for new concrete and mortars	- Not suitable
	Flooring	- Suitable (if not bonded)	- Aggregates for road layers	

Recovery patterns for gypsum are summarized in Table 5.6 according to the references indicated in Chapter 3 (see 3.2.5).

Table 5.6. Recovery scenarios for gypsum.

Material	Component/Service	End-of-life scenarios		
		Reuse	Recycling	Incineration
Gypsum	Plaster and finishing	- Not suitable	- Portland cement agent (depending on contamination level) - Road foundation - oil stabilization - Soil amendment - Composting amendment	- Not suitable
	Plasterboard (walls and ceilings)	- Suitable (depending on reclaim process)	- Plasterboard - Portland cement agent (depending on contamination level) - Road foundation - Soil stabilization - Soil amendment - Composting amendment	- Not suitable

Recovery patterns for glass are summarized in Table 5.7 according to the references indicated in Chapter 3 (see 3.2.6).

Table 5.7. Recovery scenarios for glass.

Material	Component/Service	End-of-life scenarios		
		Reuse	Recycling	Incineration
Flat glass	Windows	- Suitable (resizing is needed)	- Fine aggregates for new concrete and mortars - Cement substitute - Aggregates for paving stone, masonry blocks and architectural elements - Abrasive - Filtration media, - Filler in paints and plastics; - Binder in bricks, ceramic, and pottery.	- Not suitable

Recovery patterns for thermal and moisture protection materials are summarized in Table 5.8 according to the references indicated in Chapter 3 (see 3.2.7).

Table 5.8. Recovery scenarios for thermal and moisture protection materials.

Material	Component/Service	End-of-life scenarios		
		Reuse	Recycling	Incineration
Rockwool	Acoustic and thermal insulation	- Suitable	- New Rockwool panels - Aggregates	- Not suitable
Polystyrene	EPS and XPS panels for thermal insulation	- Suitable (if not bonded or blended)	- Polymers recycling (see 0)	- Difficultly incinerated due to bonding or blinding
Asphalt	Waterproofing membranes	- Not suitable	- Not suitable	- Difficultly incinerated due to bonding or blinding
PVC	Waterproofing membranes	- Not suitable	- Polymers recycling (see 0)	- Difficultly incinerated due to bonding or blending

Recovery patterns for asphalt are summarized in Table 5.9 according to the references indicated in Chapter 3 (see 3.2.8).

Table 5.9. Recovery scenarios for asphalt.

Material	Component/Service	End-of-life scenarios		
		Reuse	Recycling	Incineration
Asphalt	Road pavements	- Not suitable	- New asphalt mixes - Aggregates for new pavements	- Not suitable

Recovery patterns for timber and engineered wood are summarized in Table 5.10Table 5.9 according to the references indicated in Chapter 3 (see 3.2.9).

Table 5.10. Recovery scenarios for timber and engineered wood.

Material	Component/Service	End-of-life scenarios		
		Reuse	Recycling	Incineration
Timber	Structural frame	- Suitable (resizing if needed)	- Flooring - Doors - Chips for wood composites and lightweight mortars - Chips for landscaping - Soil amendment	- Energy recovery
	Flooring	- Suitable (resizing if needed)	- Chips for wood composites and lightweight mortars - Chips for landscaping; - Soil amendment	- Energy recovery
	Glued-laminated structural components	- Suitable (resizing if needed)	- Flooring - Chips for wood composites and lightweight mortars - Chips for landscaping; - Soil amendment	- Energy recovery (depending on contaminants)
Wood chips	Boards: particle board, plywood, flake board, fibreboard	- Difficultly suitable	- Chips for lightweight mortars - Not suitable for new panels production - Chips for landscaping; - Soil amendment	- Energy recovery (depending on contaminants)
	Plastic lumber	- Suitable	- Polymers recycling (see 0)	- Energy recovery

Recovery patterns for thermoplastic polymers are summarized in Table 5.11Table 5.9 according to the references indicated in Chapter 3 (see 3.2.10).

Table 5.11. Recovery scenarios for thermoplastic polymers.

Material	Component/Service	End-of-life scenarios		
		Reuse	Recycling	Incineration
Polyvinyl chloride (PVC)	Window and door frames	- Suitable (resizing if needed)	- PVC granulate - Fillers - HCl, benzene and toluene	- Energy recovery
	Floor coverings	- Suitable (if not bonded)		
	Roofing sheets	- Not suitable		
	Pipes	- Not suitable		
Polystyrene (PS)	Thermal insulation panels (extruded or expanded)	- Suitable (if not bonded or blended)	- PS granulate - Aggregates - Fillers - Styrene and its oligomers	- Energy recovery
Polypropylene (PP)	Pipes	- Not suitable	- PS granulate - Fillers - Vaseline - Olefins - Gases and light oils	- Energy recovery
Polyethilene (PE)	Pipes	- Not suitable	- PE granulate - Fillers - Plastic lumber - Waxes - Paraffin oils - Olefins - Gases and light oils	- Energy recovery
	Acoustic insulation roll sheets	- Not suitable	- Difficultly recyclable due to bonding or blending	- Difficultly incinerated due to bonding or blending

Recovery patterns for thermoset polymers are summarized in Table 5.12 according to the references indicated in Chapter 3 (see 3.2.10).

Table 5.12. Recovery scenarios for thermoset polymers.

Material	Component/Service	End-of-life scenarios		
		Reuse	Recycling	Incineration
Epoxy	Flooring	- Suitable (if not bonded)	- Fillers - Recycled resin	- Energy recovery
	Adhesives (concrete, tiles, wood, glass) Coatings (concrete, metals, mortars)	- Not suitable	- Difficultly recyclable due to blending	- Difficultly incinerated due to blending
Silicone	Sealants (construction joints) Water repellent	- Not suitable	- Difficultly recyclable due to blending	- Difficultly incinerated due to blending

Recovery patterns for polyurethane are summarized in Table 5.13 according to the references indicated in Chapter 3 (see 3.2.10).

Table 5.13. Recovery scenarios for polyurethane (PU).

Material	Component/Service	End-of-life scenarios		
		Reuse	Recycling	Incineration
Polyurethane (PU)	Flooring	- Suitable (if not bonded)	- Fillers - PU granulate	- Energy recovery
	Adhesives (plywood, wood frames) Sealants (construction joints) Coatings (concrete, weathering resistant applications)	- Not suitable	- Difficultly incinerated due to blinding	- Difficultly incinerated due to blending

Recovery patterns for steel and stainless steel are summarized in Table 5.14 according to the references indicated in Chapter 3 (see 3.2.11).

Table 5.14. Recovery scenarios for steel and stainless steel.

Material	Component/Service	End-of-life scenarios		
		Reuse	Recycling	Incineration
Steel	Structural elements	- Suitable (resizing if needed)	- New steel	- Not suitable
	Window frames	- Difficultly suitable	- New steel	- Not suitable
	Cladding, covering, roofing, and piping	- Not suitable	- New steel	- Not suitable

Recovery patterns for steel and stainless steel are summarized in Table 5.15 according to the references indicated in Chapter 3 (see 3.2.12).

Table 5.15. Recovery scenarios for non-ferrous metals.

Material	Component/Service	End-of-life scenarios		
		Reuse	Recycling	Incineration
Aluminium	Window frames	- Difficultly suitable	- New aluminium	- Not suitable
	Cladding, covering, roofing, and piping	- Difficultly suitable	- New aluminium	- Not suitable
Copper	Cladding, covering, roofing, and piping	- Not suitable	- New copper	- Not suitable
Zinc	Cladding, covering, roofing, and piping	- Not suitable	- New zinc	- Not suitable

(4) Recovery Rates

Recovery rates values establishes the common amount of materials that might be recovered during deconstruction operations, considering the losses of materials in those processes.

Reference indicators for Recovery Rates for materials and components are usually estimated according to the normal construction techniques applied.

Among others, material losses might occur due to several constraints, such as:

(i) Type of connections between materials or components;
(ii) Contamination;
(iii) Small pieces mixed in debris;
(iv) Deconstruction techniques.

Recovery rates are expressed as a percentage of the total embodied mass for each type of material or component that is recovered.

References and recovery rates values for the proposed Model are described and established in Chapter 3. For the Model's purpose, it was established that the recovery rate would be the best value found for each material included in the survey (see Table 5.16). For those materials for which no data were available, the mean value for all other materials was considered as a reference, which was calculated as 90.0%.

Table 5.16. Estimated Recovery Rate (RR) for selected building materials.

Material/Component	Best Estimated RR (%)
Aluminium	95.0
Bricks	90.0
Concrete	93.0
Concrete blocks	85.0
Copper	95.0
Doors	71.0
Flooring	78.0
Glass	93.0
Mineral wool	93.0
Mortar	90.0
Paint	93.0
Plaster	90.0
Plasterboard	95.0
Plastic (PVC)	93.0
Roof tiles	93.0
Steel (reinforcing)	93.0
Steel (structural)	97.0
Tiles	75.0
Timber and wood products	93.0
Windows	73.0

(5) Specific Emergy

Specific Emergy is a property of materials, considered as the memory of the amount of materials and energy spent in their production.

Higher Specific Emergy values correspond to more complex or high quality materials that are able to have high quality mechanical and durability performances, such as steel, concrete, or plastics. Lower Specific Emergy values correspond to materials made from renewable resources such as non-composite wood products, which may have limitations on their performance.

Accuracy for Specific Emergy values is constrained by the level of detail of the Life Cycle Inventories to be used for calculations. The flows considered crossing the system boundaries will also influence the results. For example, human labor and machinery may be or not considered in Specific Emergy calculations. However, values found in the literature and estimated in this study showed a small influence of these flows on the overall results.

Ultimately, different manufacturing processes and quality of data provided by Life Cycle inventories showed to have more influence on the overall results for the Specific Emergy of a given material or component.

Chapter 6 presents a set of Specific Emergy calculations for materials and components for which there were no previous values or for which it was considered that accuracy could be improved. In Appendix C are indicated the overall reference values for Specific Emergy and Transformities used in this study.

5.4.2 *Building configuration analysis*

A second set of information relies on data, which are the proposed Model variables for the object under analysis, such as a building system (e.g. wall, roof, façade) or an entire building. Variable values are not intrinsic properties of materials and components. Variable values are settled by the user, and depend on design decisions that will influence the overall results of the proposed Model, such as constructions techniques and types of connections. Ultimately, design decisions also influences the options on End-of-life Scenario definition and the recovery pattern for each material and component.

These data include the following issues:

(i) Embodied mass flow;
(ii) Lifespan;
(iii) Useful life;
(iv) Types of connections between materials or components;
(v) Assembly sequences;
(vi) End-of-life Scenario;
(vii) Substituted materials.

The output data of these variable conditions will be used in the calculation of the Deconstruction Effectiveness index (DE).

The relationships between these topics are also significant for the overall result provided by the proposed Model, because output data of a single parameter may be constrained by conditions that depend on other parameters. This applies for instance to the following relationships:

(i) Embodied mass of a building is a condition of the Lifespan and Useful Life parameters;

(ii) Outputs of Useful Life may be constrained by types of connections employed or by the assembly sequences in which materials are placed into the building or building element;

(iii) End-of-life Scenarios may be constrained by Useful Life or by the types of connections employed.

For the improvement of part or the overall design solution, in order to compare and evaluate solutions for decision-making, the user may change the inputs to the proposed Model variables.

(1) Embodied mass flow

Embodied mass flow is the result of accounting the overall input of each material and component that is supposed to be settled during the construction phase. In traditional building projects, this information is obtained by quantity surveying. However, in projects developed using a Building Information Modeling (BIM) platform, this information is easily obtained and updated in real time as decisions on building design are made.

All different quantities of materials and components are converted into the same unit of mass, based on materials density property.

For Emergy Accounting purposes, the unit for expressing Embodied Mass for each material and component is the gram.

(2) Lifespan

In this study, the Lifespan of a building is considered as the time that it is expected to be used before being demolished, deconstructed, or disassembled. It may also be defined as the Life Cycle period of the building or building element under assessment.

In the framework of the proposed Model, Lifespan is an option made by the user regarding his expectations for the time the building is considered to last or to be needed. If the building is designed for an exact Lifespan demand, then the Deconstruction Effectiveness index become more accurate. However, if there are no special requirements on Lifespan, this may be considered as a generic value according to what is defined in standards for different building types, such as commerce, residential, offices or industrial premises.

Options on Lifespan influence the Deconstruction Effectiveness index by afecting the adequateness of Service Lives of materials and components to the required building cycle. Materials and components for which their Service Lives equal or minimize the number of replacements during the building cycle will be preferable, since they will generate less outflows of materials. For the overall improvement of the solution, adjustments on Service Lives to meet Lifespan and to minimize material replacements by changing initial options on materials and components for a given function will improve the Deconstruction Effectiveness index.

(3) Useful Life

It spite of the data on Forecast Service Life for materials and components collected in the database of the proposed Model, it is necessary to further verify during the building or building element analysis task if materials and components have to be removed before reaching their Service Life. In that case, data on Forecast Service Life may have to be adjusted according to the period in which the materials will be replaced.

Due to materials position in the technological configuration of a building and to the type of connections employed, not always the Forecast Service Life of a material or component will match the time a material or component would effectively be useful. Materials or components with longer Service Lives may have to be removed due to the replacement of materials with shorter Service Lives. If disassembly is not possible, those materials with longer Service Lives cannot be put back into the building.

Thus, the concept of Useful Life is introduced for a better evaluation of materials flow within a building system. Useful Life is defined as the period after which a material or component will have to be removed or replaced before reaching its Forecast Service Life, due to obsolescence or due to overall maintenance and adaptive operations.

Considering Useful Life definition, two scenarios become possible in life cycle coordination:

(i) Useful Life is shorter than Forecast Service Life;
(ii) Useful Life matches Forecast Service Life.

These two scenarios influence options on materials and components recovery. In the first scenario, reuse becomes the best option for materials and components recovery, while on the other one, recycling becomes the best possible option to be considered.

Thus, Service Life Planning helps to identify service life requirements for a building and to improve building design by adjusting different life cycles of materials and components in order to maximize their use, to minimize the number of replacements, and to improve recovery patterns.

(4) Type of connections

Connections between materials or components are one of the main factors that will influence salvageability and the recovery patterns of materials and components.

Choices regarding materials and components connections in building design are often constrained by technical factors such as available technologies and need of specialized tasks. Costs and working time are also factors that may influence decisions on connections.

However, in the context of the proposed Model and Building Deconstruction approach, the most important property of a connection is its reversibility. Enhancing reversibility properties of connections will maximize salvageability and quality, by allowing easy separation of materials and components.

Thus, in order to simplify the proposed Model procedures, the different types of connections are set in two major groups according to their reversibility:

(i) Open connections (OC): mechanical connections, such as bolted snapped, mated, and striped;

(ii) Closed connections (CC): adhesive and weld connections, such as glued and sealed, welded, soldered, and cemented connections.

Despite the non-reversibility of the connections employed, in some cases materials and components may be partially reused. Such is the case of soldered steel sections that may be cut off and easily adapted to a new use or relocated in another building.

In the proposed Model, connections are identified by analyzing precedent relationships between material, components, and subassemblies. Often, materials and components are connected to others that are not part of the same element, what might hinder disassembly.

(5) Assembly sequences

Assembly sequences of materials and components in building's configuration influences the transformation capacity of the building system, by disabling or enabling maintenance, repair, and adaptive operations. Ultimately, assembly sequences determine building deconstruction or building disassembly sequence options, being a determinant factor to maximize materials and components recovery and to improve the overall quality of recovered materials.

Assembly sequences describe the hierarchical relation between different materials and components, and enhance the functional decomposition of the building or building element. By analyzing assembly sequences and functional clusters, a set of conditions influencing building transformation or deconstruction/disassembly procedures may be highlighted:

(i) If a functional sub-system, such as a roof or an external wall, is assembled independently from other functional sub-systems, renewal or adaptive operations will be easily performed;
(ii) If a set of materials is assembled as an independent functional cluster, such as a window or an infrastructure, its repair or deconstruction will not be constrained by other functional clusters;
(iii) If a cluster of materials is assembled according to their Service Lives hierarchy, materials with longer Service Lives will not be damaged if materials with shorter Service Lives have to be repaired or replaced.

In the proposed Model, assembly sequence analysis is performed according to a functional decomposition of the building and by analyzing hierarchical relations between materials or components.

The functional decomposition considered in the Model divides the building system in a set of functional sub-systems, and the later in a set of functional clusters, which are divided in turn in materials and components:

(i) Foundations;
(ii) Structural frame;
(iii) Façades and roofs;
(iv) Floors;
(v) Interior partition;
(vi) Ceilings.

(6) End-of-life Scenarios (ELS)

The Model comprises the identification of the most feasible End-of-life Scenario for each recovered material or component. The End-of-life Scenario allows to identify the raw material for which a recovered material or component will be a substitute.

In the proposed Model, End-of-life Scenarios are set in four simplified options:

(i) Reuse;
(ii) Recycling;
(iii) Heat recovery;
(iv) Landfill.

The general recovery conditions/constraints to establish a correspondence between a material or component and an End-of-life Scenario are based in its Forecast Service Life, Useful Life, type of connections employed, and its composition, i.e. being or not a composite material or not containing hazardous substances. These properties influence the overall quality of the salvaged materials and components, not just by constraining their allocation to an End-of-life Scenario, but also by constraining feasible technical recovery processes.

Thus, recovered materials are allocated to the four different End-of-life Scenarios if fulfilling certain established conditions according to their properties.

(a) Reuse scenario

Within the proposed Model, the reuse scenario is considered for those materials and components that fulfill all or part of the following conditions (see Figure 5.4):

(i) Whose Forecast Service Life is longer than building Lifespan;
(ii) Whose Useful Life is shorter than its Forecast Service Life or Lifespan of the building;
(iii) That can be disassembled or partially removed;
(iv) That keep their shape or function after being disassembled or partially removed;
(v) Not being or not incorporating hazardous materials.

Structural and demountable components are usually suitable for reuse, such as steel sections, wood and engineered wood sections, and assembled precast concrete elements, as long as they meet standard requirements.

Non-structural materials may also be suitable for reuse such as finishing materials that could be resized if needed (e.g. wood floors, glass panels, window and door frames, or metallic panels).

Non-disassemblable elements might be cut off without losing their shape, and partially reused afterwards for a same or a different purpose.

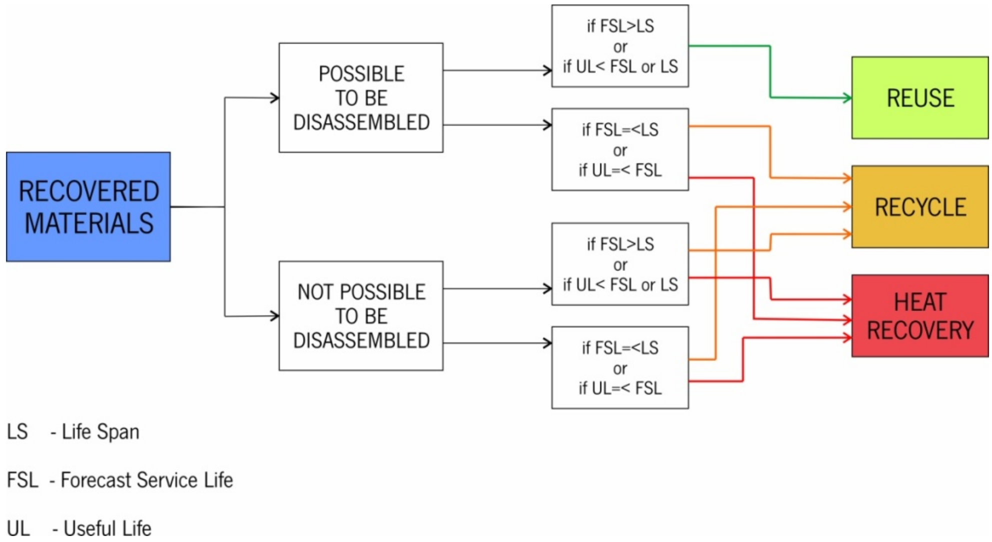


Figure 5.4. Allocation of recovered materials to end-of-life scenarios.

(b) Recycling scenario

In the proposed Model, the recycling scenario option is to be considered for those materials and components that fulfill all or part of the following criteria (see Figure 5.4):

(i) Whose Forecast Service Life is longer than building or building element's Lifespan but disassemblage is not possible;
(ii) Whose Forecast Service Life is equal or shorter than building or building element's Lifespan;
(iii) Whose Useful Life matches or is shorter than their Forecast Service Life;
(iv) That cannot be disassembled;
(v) That do not keep their shape in spite of being disassembled;
(vi) That can be separated by mechanical or chemical processes if being a composite material, or recycled as it is;
(vii) That can be cleaned if being a contaminated material;
(viii) Not being or not incorporating hazardous materials.

Disassembly possibility is not a primary condition for recycling if mechanical or chemical processes are applied for separation and cleaning. Good examples are the cases of separating paper from gypsum in plasterboard recycling, or steel from concrete in structural concrete recycling.

Materials that are not feasible to be separated for recycling purposes, such as glued materials will be allocated to Heat Recovery or Landfill scenarios, depending on their composition and level of contamination.

(c) Heat recovery

The Heat Recovery scenario is considered as a feasible option for those materials that are not suitable for reuse or recycling purposes, but are recovered for energy production through combustion or chemical processes (see Figure 5.4). Output products of combustion may also be recovered in these processes.

Discarded wood and plastic materials that are not contaminated are suitable for this purpose. Plastics combustion is a common practice for energy recovery as a heat source, as well as for recovery of secondary products as inert slag or HCl, when air toxic releases from combustion are filtered.

(d) Landfill

The Landfill scenario is considered as the final option for those materials that are not suitable for the three previous scenarios. Materials not removed in separate, presenting chemical and physical contamination, non-separable composite materials, and materials classified as hazardous are allocated to this End-of-life Scenario.

Landfill scenario may include combustion for mass reduction of waste and specific treatments for inertising or lowering leachate in hazardous materials.

(7) Substituted materials

The recovery scenarios defined according to the predicted quality of the salvaged materials, enables to close the loop by substituting raw materials or components. This procedure follows the information gathered in the proposed Model database concerning the possible recovery patterns for each material or component.

The proposed Model considers that substitution of raw material is the possible option, disregarding costs of recovery processes. However, the application of the Model may constrain the available recovery paths, by establishing cost and technological boundaries to the selection of recovery options.

In reuse scenarios, materials or components may substitute the same product with the same function or the same product with a different function, or even part of a subassembly with the same or different function (see Figure 5.5). Reuse of materials and components may comprise disassembly and reassembly of components of a same or different product. Operations of disassembly and reassembly of products may include repair and upgrade actions of materials or components.

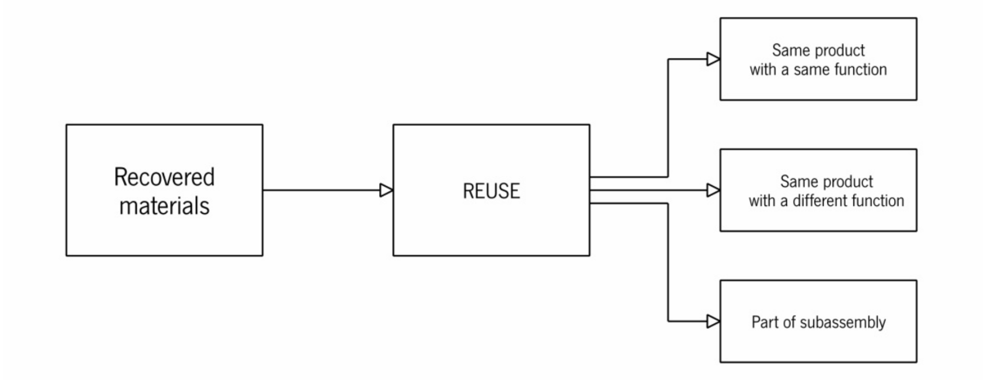


Figure 5.5. Allocation of substituted materials in reuse scenarios.

In recycling scenarios, materials might be allocated to several recycling paths according to their quality and feasible and available recycling technologies (see Figure 5.6). Recycling of materials and components may comprise chemical or mechanical separation procedures in order to obtain non-contaminated recyclates. Recyclates may be a substitute of raw materials for the same material production or a substitute for a raw material in a different material manufacture. Recycling materials for different purposes may occur at different levels:

(i) Downgrading level: recyclates are used for the production of a lower quality material;

(ii) Same level: recyclates are used for the production of a same quality material, that can be different or not;

(iii) Upgrading level: recyclates are used for the production of a higher quality material.

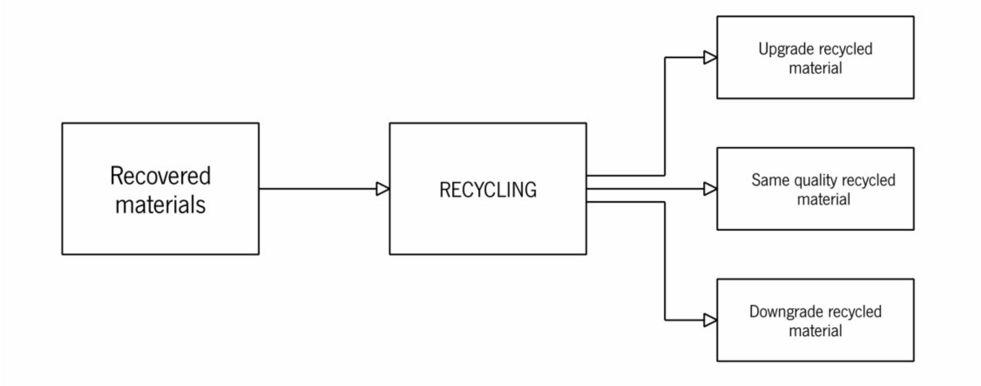


Figure 5.6. Allocation of substituted materials in recycling scenarios.

In Heat Recovery scenarios, the incinerated materials will be a substitute for the production of the same amount of embodied energy (heat) (see Figure 5.7). For the proposed Model purposes, secondary products from combustion are also accounted as substituted materials.

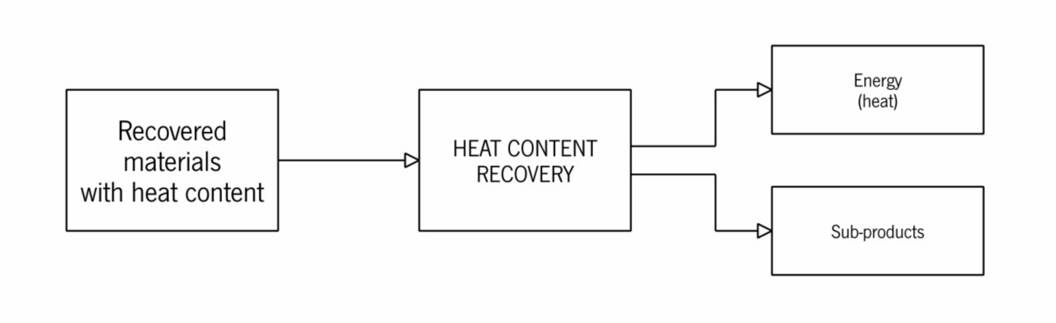


Figure 5.7. Allocation of substituted materials in heat recovery scenarios.

Common examples of substituted materials that might be considered in the proposed Model's application are the following:

(i) For concrete debris recycling in aggregates production, the raw material substituted by recycled aggregates would be a natural stone, such as granite (downgrading recycling level);

(ii) For massive wood recycling in wood-plastic composites production or engineered wood panels such as plywood or oriented strand board, the raw material substituted would be virgin wood logs (upgrading recycling level);

(iii) For steel recycling in steel production, the raw material substituted would be iron ingot (same recycling level);

(iv) For plasterboard recycling in plasterboard production, the raw materials substituted would be natural gypsum (same recycling level).

5.4.3 *The Deconstruction Effectiveness index*

After the analysis of the general constraints and the allocation of data, the overall information is gathered to proceed to the next step of the proposed Model.

The third step of the Model concerns the calculations of the Deconstruction Effectiveness index by following a set of five equations. This set of equations expresses the principles of Emergy accounting and the procedures for building system's analysis.

The units applied to the equations are the following:

(i) Emergy is expressed in seJ;
(ii) Specific Emergy is expressed in seJ/g;
(iii) Mass is expressed in g;
(iv) Recovery Effectiveness (RE) is expressed in seJ.

(1) Emergy of materials and components

The first equation regards the accounting of the Emergy of a material and component during its lifespan:

$$Emergy\ M_i = (Mass\ M_i\ \times Specific\ Emergy\ M_i)\ \times N.^{\underline{o}}\ of\ Inputs\ M_i \qquad (1)$$

where: M_i = material or component under assessment; and $N.^{\underline{o}}\ of\ Inputs\ M_i$ = total number of inputs of M_i (initial input and replacements during Lifespan).

According to the proposed Model, if the forecast service or useful lives are less that the lifespan, the Emergy of the material or component is accounted as a function of the number of inputs of the material during the lifespan considered.

(2) Total Emergy of the materials inputs

The second equation aggregates the Emergy inputs of all the materials and components within the building or building element:

$$Emergy\ B = \sum_{\mathrm{i}=1}^{n} Emergy\ M_i \qquad (2)$$

where M_i = material or component under assessment; and B = building or building element under assessment.

(3) Recovery Effectiveness of a material or component (RE)

The third equation describes the Emergy of the raw resources or components that are saved by the recovered materials according to the most feasible end-of-life scenarios:

$$RE\ M_i = (Mass\ SM_i \times Specific\ Emergy\ \ SM_i) \times N.^{\underline{o}}\ of\ Inputs\ M_i \qquad (3)$$

where M_i = material or component under assessment; SM_i = best option for which M_i will be a substitute; $N^{\underline{o}}\ of\ Inputs\ M_i$ = total number of inputs of M_i (initial input and replacements during Lifespan); and $RE\ M_i$ = recovery effectiveness of a material or component.

In the case of the reuse scenario, it is considered that the recovered material will replace the same initial product or assembly. For example, a recovered steel section is reused as a steel section.

(4) Total recovery effectiveness of a building or building component

The fourth equation aggregates the Emergy that is saved by materials recovery during the lifespan considered:

$$RE\ B = \sum_{i=1}^{n} RE\ M_i \tag{4}$$

where $RE\ M_i$ = recovery effectiveness of a material or component; and $RE\ B$ = recovery effectiveness of the building or building element.

(5) Deconstruction Effectiveness (DE)

The Deconstruction Effectiveness index is obtained as the ratio of the recovery effectiveness of materials for the building or building element and the total Emergy of the building or building element:

$$DE = \frac{RE\ B}{Emergy\ B} \tag{5}$$

where DE = Deconstruction Effectiveness; $RE\ B$ = recovery effectiveness of the building or building element; and $Emergy\ B$ = total Emergy of the building or building element.

The values of DE range between 0 and 1, being 0 the least effective and 1 the most effective.

5.4.4 *Solution improvement*

The fourth and final step of the proposed Model framework is the solution improvement. The information generated by the Model acts as a feedback to insert changes into the building design in order to achieve a better Deconstruction Effectiveness index.

Changes in the type of connections, materials and components hierarchy, and materials and components employed that can improve the overall results.

This step is quite important for decision-making and for comparing different technical building solutions.

5.5 *Evaluation of the proposed Model*

The proposed Model is evaluated by assessing several case studies, both for building element and whole building. The evaluation and discussion is presented in Chapter 7.

By applying the proposed Model to a building element, it is easier to evaluate the behavior of the Model when changes are made to the recovery rates, lifespan, and end-of-life scenarios.

The proposed Model is applied to 3 types of internal wall systems for evaluating building elements

(i) Brick masonry;
(ii) Plasterboard;
(iii) Wood frame.

By applying the proposed Model to an entire building, it is possible to evaluate the overall behavior regarding the complexity of the information. Partial changes in the internal walls were made to verify if the Deconstruction Effectiveness was sensitive to the improvement of the building design concerning disassemblability.

Furthermore, the Model is applied to three buildings with different construction principles:

(i) Concrete structural system;
(ii) Wood structural system;
(iii) Steel structural system.

CHAPTER 6

EMERGY EVALUATION OF SELECTED BUILDING MATERIALS

Necessary data to run the proposed Model includes a compilation of Specific Emergy (Emergy per mass) values for building materials. For this purpose, a set of Specific Emergy values were collected from Emergy evaluation studies published in the last few years (see Appendix C for references).

However, application of Emergy analysis to building materials and buildings is still scarce, and the Specific Emergy values available are very limited. In most cases, published Specific Emergy values for building materials refers to a generic group of materials, such as steel, paints, or plastics, and just few studies refers to transformed materials or components.

The state of the art highlights the need to make calculations for specific Emergy values for several materials, and to review some reference values in order to make them more accurate.

The major source for Specific Emergy of building materials is the work of Buranakarn (1998). Thus, a set of Specific Emergy values have been used in following studies by several authors, and rarely have been produced new Emergy studies applied to building materials.

Values collected from references are not enough nor sufficiently accurate to be applied to the Model. For the evaluation of the case studies, Emergy evaluation of materials was done for the following materials, using existing Life Cycle Inventories:

(i) Marble tiles;
(ii) Granite tiles;
(iii) Ceramic tiles;
(iv) Plasterboard (unfinished and finished panel);
(v) Portland cement;
(vi) Concrete C20/C25;
(vii) Mortars and plasters;
(viii) Painting (finished);
(ix) Oriented Strand Board (OSB) panel;
(x) Thermoformed Expanded Polystyrene (EPS);
(xi) Aluminium (extruded profiles);
(xii) Solid wood flooring.

The Emergy Evaluation of these building materials, was based on Life Cycle Inventories of building materials production, mostly included in Life Cycle Assessment (LCA) studies. These studies brought a new and accurate source of information for Emergy Analyses studies.

The calculations were made by applying the following principles:

(i) All calculations were made without considering services, omitting human labour and machinery, because there was no coherent data and total lack of data in the Life Cycle Inventories that were used; furthermore, Specific Emergy calculations made by Buranakarn (1998) for building materials showed slight differences between Specific Emergy values including services and those not including services;

(ii) Emergy calculations were made according to Odum (2000), using the baseline of 15.83 E+24 seJ/y;

(iii) Collected Transformities and Specific Emergy values that were calculated using the baseline of 9.44 E+24 seJ/y were corrected by a 1.68 factor to match the new standard baseline;

(iv) Specific Emergy of recovered materials for recycling was considered the same as the substituted material;

(v) Inputs of a same material or energy source during different phases of production were aggregated in a same flow.

6.1 *Emergy evaluation of marble tiles (without services)*

Data for the Emergy evaluation of marble tiles were collected from an LCA study presented by Nicoletti *et al.* (2002).

The Inventory Analysis includes data on the following phases of the productive cycle: quarry operations; raw block cutting; cutting of the standard size tiles; and polishing and buffing.

Table 6.1. Emergy analysis of marble tiles (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Marble	g	2.31 E+05	2.44 E+09	5.63 E+14
2	Water	g	6.64 E+04	1.12 E+06	7.41 E+10
Fuels and electricity					
3	Electricity	J	1.14 E+08	2.92 E+05	1.30 E+13
4	Thermal energy	J	9.10 E+06	1.11 E+05	1.01 E+12
	Total EMERGY				5.97 E+14
	1 m^2 of marble tiles (1.8 cm thickness)	g	4.95 E+04	1.21 E+10	5.97 E+14

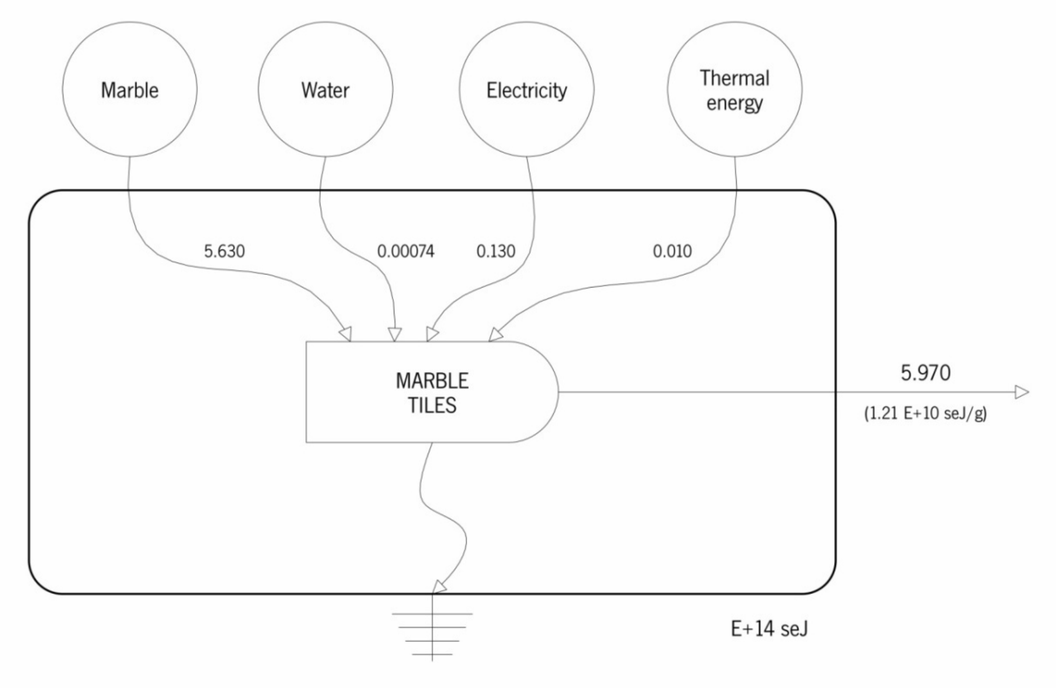


Figure 6.1. Emergy diagram of marble tiles (without services).

6.2 *Emergy evaluation of granite tiles (without services)*

Data for Emergy evaluation of granite tiles were established according to the Life Cycle Inventory of marble tiles published by Nicoletti *et al.* (2002), assuming that manufacturing processes are the same in general.

Data input for granite were corrected according to the density of the material. Data for water and energy consumption were considered as the same.

Table 6.2. Emergy analysis of granite tiles (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Granite	g	2.24 E+05	8.40 E+08	1.88 E+14
2	Water	g	6.64 E+04	1.12 E+06	7.41 E+10
Fuels and electricity					
3	Electricity	J	1.14 E+08	2.92 E+05	1.30 E+13
4	Thermal energy	J	9.10 E+06	1.11 E+05	1.01 E+12
	Total EMERGY				2.02 E+14
	1 m^2 of granite tiles (1.8 cm thickness)	g	4.80 E+04	4.21 E+09	2.02 E+14

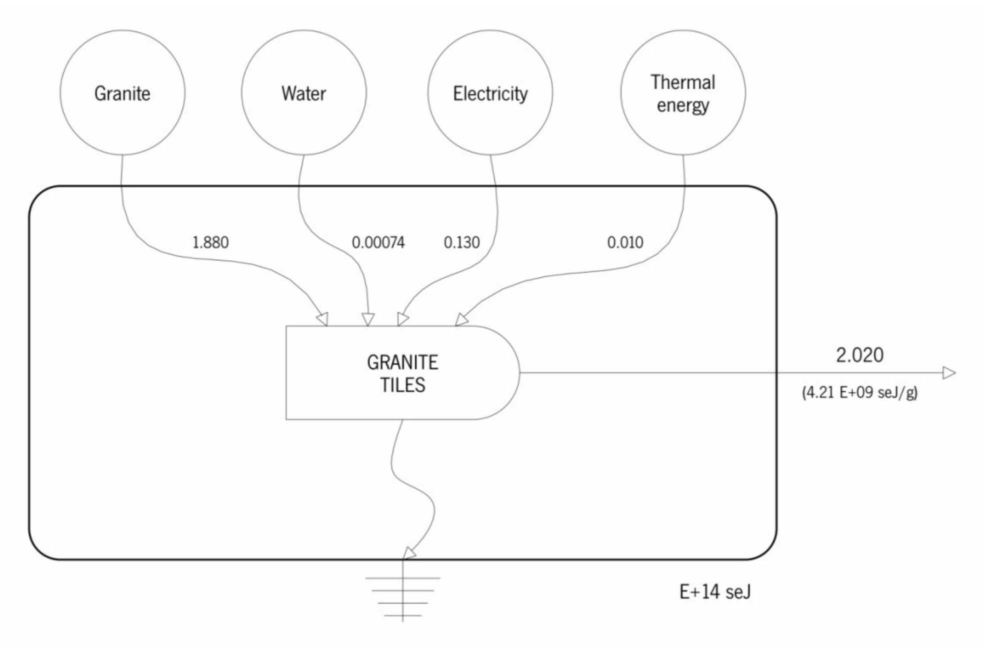


Figure 6.2. Emergy diagram of granite tiles (without services).

6.3 *Emergy evaluation of ceramic tiles (without services)*

Data for the Emergy evaluation of ceramic tiles were collected from an LCA study presented by Nicoletti *et al.* (2002). The Inventory Analysis includes data on the two different stages of the productive cycle:

(i) Body preparation: raw materials acquisition, mixture preparation, forming, and drying;

(ii) Glaze manufacturing: raw materials acquisition, frit preparation, enamelling and firing of the glazed body, and waste water purification.

Table 6.3. Emergy analysis of ceramic tiles (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Clay	g	8.80 E+03	3.36 E+09	2.96 E+13
2	Feldspars	g	4.89 E+03	8.40 E+08	4.11 E+12
3	Limestone	g	2.93 E+03	1.68 E+09	4.92 E+12
4	Siliceous sand	g	2.81 E+03	2.24 E+09	6.29 E+12
5	Frit (glazing)	g	1.13 E+03	1.68 E+09	1.90 E+11
6	Water	g	2.40 E+04	1.12 E+06	2.68 E+10
Fuels and electricity					
7	Electricity	J	2.03 E+07	2.92 E+05	5.91 E+12
8	Oil fuels	J	2.24 E+06	1.11 E+05	2.48 E+11
9	Natural gas	J	5.20 E+07	8,06 E+04	4.19 E+12
10	Methane	J	5.29 E+07	8.06 E+04	4.27 E+12
	Total EMERGY				5.97 E+13
	1 m^2 of ceramic tiles	g	1.80 E+04	3.32 E+09	5.97 E+13

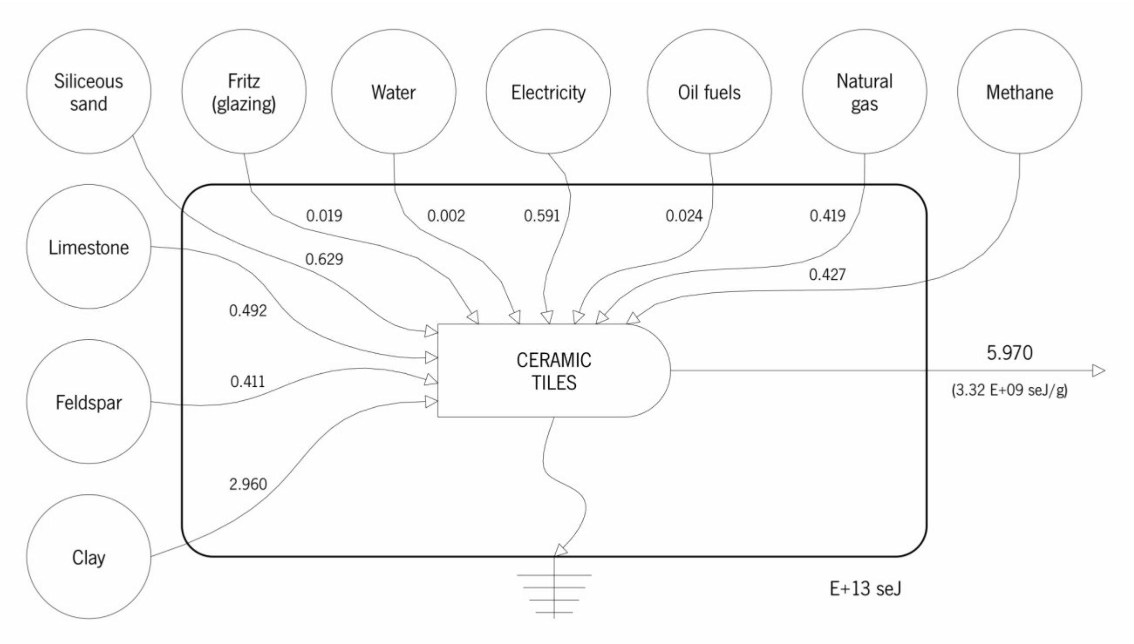


Figure 6.3. Emergy diagram of ceramic tiles (without services).

6.4 *Emergy evaluation of plasterboard (without services)*

Data for the Emergy evaluation of plasterboard were collected from the LCA report published by Fisher (2008) for the Waste & Resources Action Programme. The LCA covers all the production phases (extraction of raw materials, plasterboard, paper, chemical additives, packaging materials), use in construction, collection of construction waste, and recycling and recovery of gypsum.

The following stages of production were considered for the Emergy evaluation:

(i) Primary gypsum extraction and secondary gypsum recovery;
(ii) Pre-processing of raw materials (stucco production);
(iii) Production of papers;
(iv) Plasterboard production.

For the accuracy of the final results, production of stucco and facing paper were also evaluated. The Specific Emergy calculated for stucco and facing paper were included in plasterboard evaluation. Further, finished plasterboard, including final gypsum layer, was also evaluated. A decrease in the Emergy per mass of finished plasterboard may be observed, if compared with Specific Emergy of plasterboard.

Unot Solar Emergy for paper was considered according to its heat content and not to its mass, since there was no Specific Emergy value available in existing studies.

6.4.1 *Emergy evaluation of stucco (without services)*

Table 6.4. Emergy analysis of stucco (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Gypsum	g	1.23 E+06	1.68 E+09	1.14 E+15
Fuels and electricity					
2	Electricity	J	1.18 E+08	2.92 E+05	3.43 E+13
3	Natural gas	J	8.71 E+08	8,06 E+04	7.03 E+13
4	Oil fuels	J	9.68 E+07	1.18 E+05	1.14 E+13
	Total EMERGY				2.18 E+15
	1 ton of stucco	g	1.00 E+06	2.18 E+09	2.18 E+15

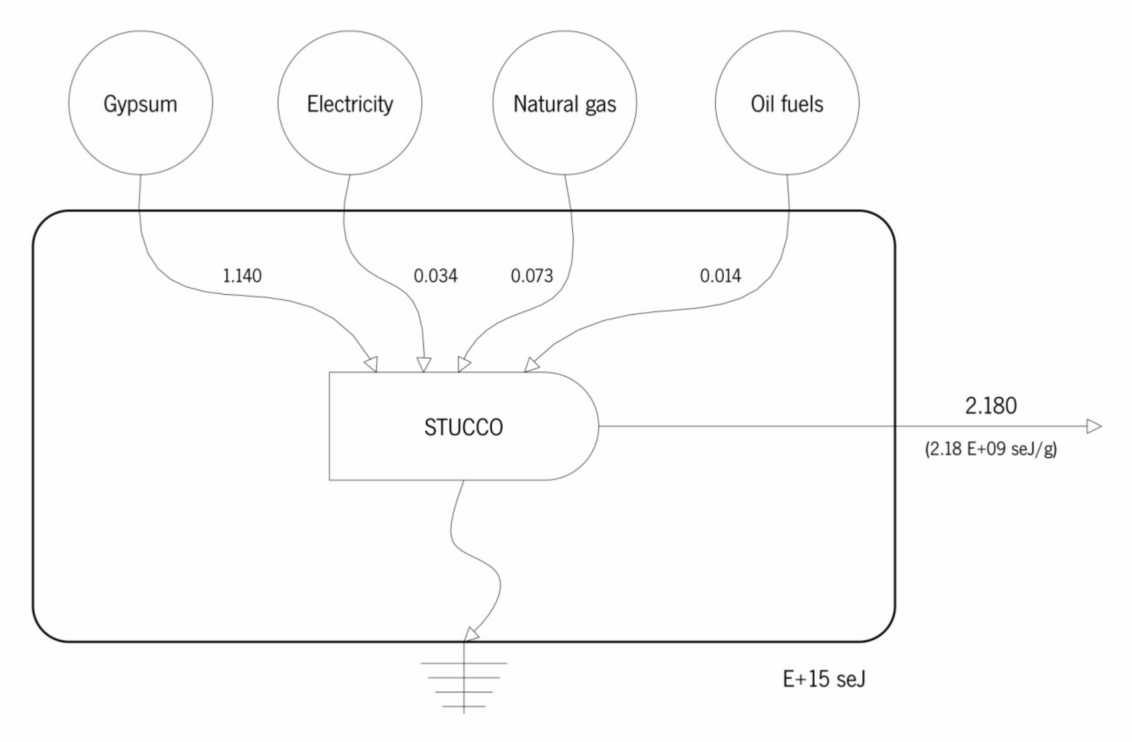


Figure 6.4. Emergy diagram of stucco (without services).

6.4.2 *Emergy evaluation of facing paper (without services)*

Table 6.5. Emergy analysis of facing paper (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Virgin paper	J	3.55 E+08	3.61 E+05	1.28 E+14
2	Recycled paper	J	1.85 E+10	3.61 E+05	6.66 E+15
3	Starch	g	6.80 E+03	6.38 E+08	4.34 E+12
4	Biocide	g	9.00 E+03	6.38 E+08	5.75 E+12
5	Dyes	g	3.00 E+02	6.38 E+08	1.92 E+11
6	ASA sizing	g	2.30 E+03	6.38 E+08	1.47 E+12
7	Retention polymer	g	7.00 E+02	6.38 E+08	4.47 E+11
8	Antifoaming agent	g	3.00 E+02	6.38 E+08	1.92 E+11
9	Aluminium oxide	g	4.80 E+03	1.68 E+09	8.06 E+12
10	Water (mains and river)	g	7.11 E+06	5.43 E+05	3.86 E+12
Fuels and electricity					
11	Electricity	J	1.95 E+09	2.92 E+05	5.69 E+14
12	Oil fuels	J	2.07 E+07	1.11 E+05	2.29 E+12
13	Natural gas	J	2.25 E+09	8,06 E+04	1.81 E+14
	Total EMERGY				7.57 E+15
	1 ton of facing paper	g	1.00 E+06	7.57 E+09	7.57 E+15

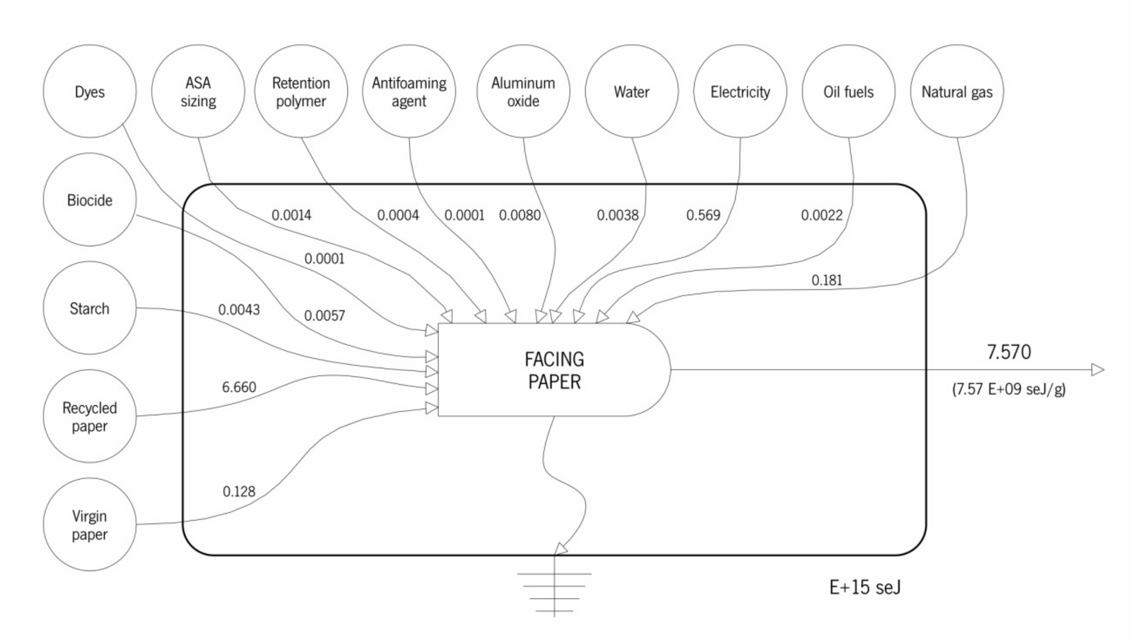


Figure 6.5. Emergy diagram of facing paper (without services).

6.4.3 *Emergy evaluation of plasterboard panel (without services)*

Table 6.6. Emergy analysis of plasterboard panel (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Stucco	J	8.59 E+05	2.18 E+09	1.87 E+15
2	Facing paper	J	4.70 E+14	7.57 E+09	3.56 E+14
3	Corn starch	g	4.00 E+03	6.38 E+08	2.55 E+12
4	Potassium sulphate	g	7.00 E+02	1.85 E+09	1.29 E+12
5	Fluidiser	g	6.00 E+02	6.38 E+08	3,83 E+11
6	Detergent (soap)	g	1.00 E+02	6.38 E+08	6.38 E+10
7	Edge glue	g	2.00 E+02	6.38 E+08	1,28 E+11
8	Waste paper	J	1.70 E+03	3.61 E+05	6.14 E+08
9	Copper sulphate	g	1.00 E+02	1.68 E+09	3.36 E+11
10	Lignin sulphonate	g	1.70 E+03	6.38 E+08	1.09 E+12
11	Ink	g	1.00 E+01	3.11 E+09	3.11 E+10
12	Nealit (fine ground gypsum)	g	5.20 E+03	1.68 E+09	8.74 E+12
13	Dextrose	g	9.00 E+02	6.38 E+08	5.75 E+11
14	Water (mains)	g	5.26 E+05	1.12 E+06	5.87 E+11
Fuels and electricity					
15	Electricity	J	9.00 E+07	2.92 E+05	2.63 E+13
16	Natural gas	J	2.02 E+09	8,06 E+04	1.63 E+14
	Total EMERGY				2.43 E+15
	1 ton of plasterboard panel	g	1.00 E+06	2.43 E+09	2.43 E+15

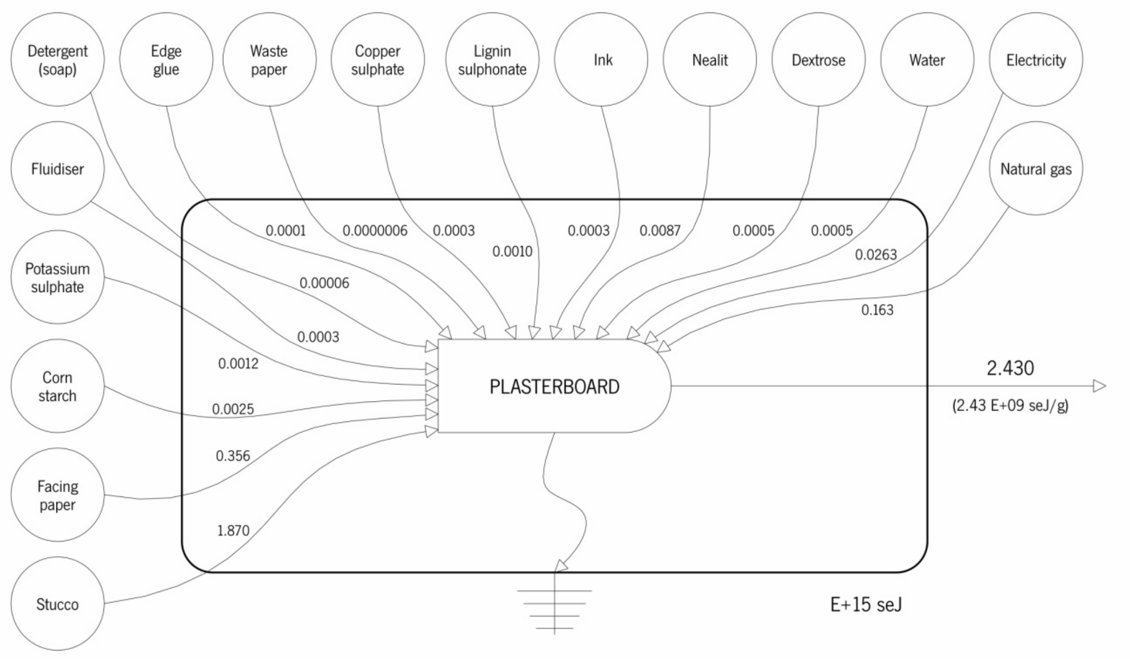


Figure 6.6. Emergy diagram of plasterboard panel (without services).

6.4.4 *Emergy evaluation of finished plasterboard panel (without services)*

Table 6.7. Emergy analysis of finished plasterboard panel (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Plasterboard	g	1.02 E+04	2.43 E+09	2.48 E+13
2	Gypsum	g	3.30 E+02	1.68 E+09	5.54 E+11
3	Water (potable)	g	1.65 E+02	7.96 E+07	1.31 E+10
	Total EMERGY				2.54 E+13
	1 m^2 finished plasterboard (13 mm thickness)	g	1.05 E+04	2.41 E+09	2.54 E+13

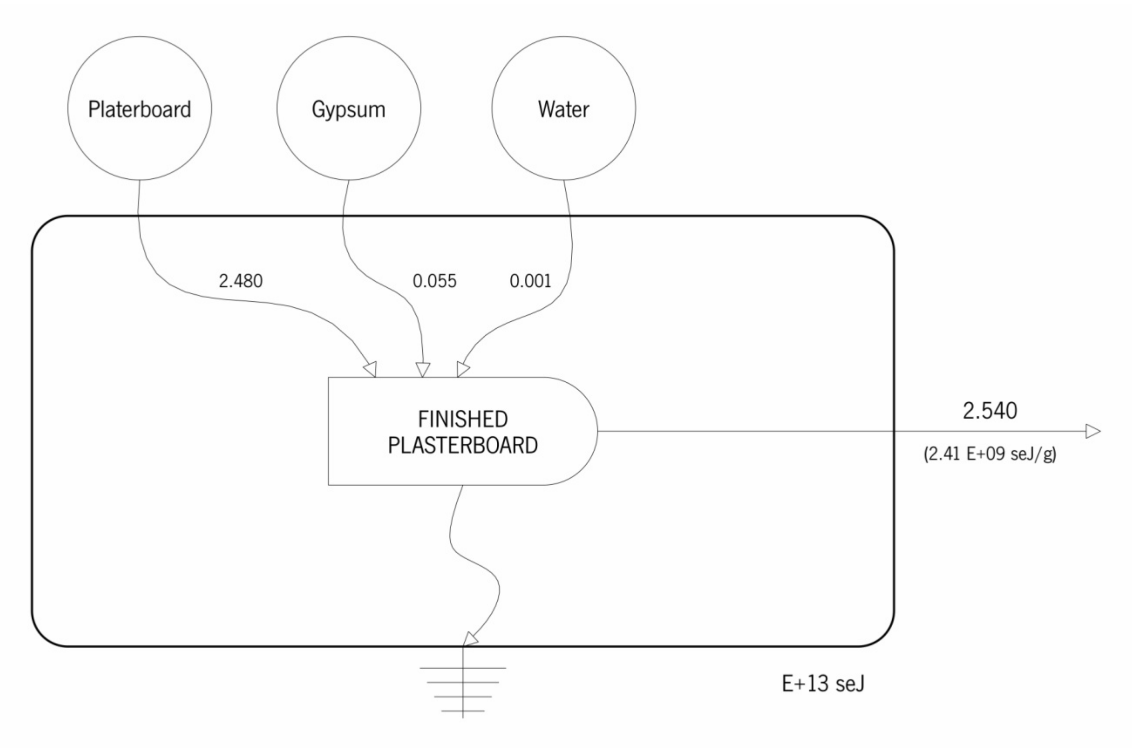


Figure 6.7. Emergy diagram of finished plasterboard (without services).

6.5 *Emergy evaluation of Portland cement (average system production without services)*

Data for the Emergy evaluation of Portland cement manufacture were collected from the LCI report developed by Marceau *et al.* (2006) for the Portland Cement Association, United States of America. The systems boundary of the Life Cycle Inventory includes the following operations:

(i) Quarry operations (extracting raw material, crushing, conveying and stockpiling);

(ii) Raw meal preparation (recovering materials from stockpiles, proportioning, grinding and blending);

(iii) Pyroprocessing (removing water, calcining limestone, mix components reaction to form clinker, cooling and clinker storing);

(iv) Finish grinding (reclaiming clinker from storage, adding gypsum, grinding to a fine powder, conveying to storage);

(v) Transportation associated with the different operations.

The Life Cycle Inventory includes data on water usage, fuel and raw materials consumption for four different cement plant processes:

(i) Wet process (ground raw materials are suspended in sufficient water to form a pumpable slurry);

(ii) Dry processes: long dry, fry with preheated, dry with preheater and precalciner (ground raw materials are dried to a flowable power and require lower thermal energy consumption).

Results for the production weighted average are also presented according to amounts of production:

(i) Wet process weighting factor: 0.165 (16.5 % of US clinker production);

(ii) Long dry process weighting factor: 0.144 (14.4 % of US clinker production);

(iii) Preheater process weighting factor: 0.158 (15.8 % of US clinker production);

(iv) Precalciner process weighting factor: 0.533 (53.3% of US clinker production).

For the Emergy evaluation, average production data were considered as inputs.

Table 6.8. Emergy analysis of Portland cement (average system production without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Limestone	g	1.17 E+06	1.68 E+09	1.96 E+15
2	Cement rock	g	2.07 E+05	1.68 E+09	3.48 E+14
3	Shale	g	5.20 E+04	1.68 E+09	8.74 E+13
4	Clay	g	6.00 E+04	3.36 E+09	2.02 E+14
5	Bottom ash	g	1.00 E+04	1.39 E+09	1.39 E+13
6	Foundry sand	g	4.00 E+03	2.24 E+09	8.96 E+12
7	Sand	g	4.00 E+04	2.24 E+09	8.96 E+13
8	Iron ore	g	1.40 E+04	2.05 E+09	2.87 E+13
9	Blast furnace slag	g	2.00 E+04	1.11 E+10	2.22 E+14
10	Slate	g	1.00 E+03	2.44 E+09	2.44 E+12
11	Others (mainly minerals)	g	2.60 E+04	1.68 E+09	4.37 E+13
12	Gypsum	g	4.90 E+04	1.68 E+09	8.23 E+13
13	Water (process)	g	8.80 E+04	1.12 E+06	9.82 E+10
14	Water (non-process)	g	7.52 E+05	1.12 E+06	8.39 E+11
Fuels and electricity					
15	Electricity	J	5.18 E+08	2.92 E+05	1.51 E+14
16	Coal	J	2.66 E+09	6.72 E+04	1.79 E+14
17	Gasoline	J	4.63 E+06	1.11 E+05	5.14 E+11
18	Liquefied petroleum gas	J	3.64 E+05	1.18 E+05	4.28 E+11
19	Middle distillates	J	4.12 E+07	1.11 E+05	4.57 E+12
20	Natural gas	J	2.30 E+08	8.06 E+04	1.86 E+13
21	Petroleum coke	J	1.01 E+09	9.07 E-04	9.19 E+13
22	Residual oil	J	1.84 E+06	1.11 E+05	2.04 E+11
	Total EMERGY				3.53 E+15
	1 ton Portland Cement (Average system production)	g	1.00E+06	3.53+09	3.53 E+15

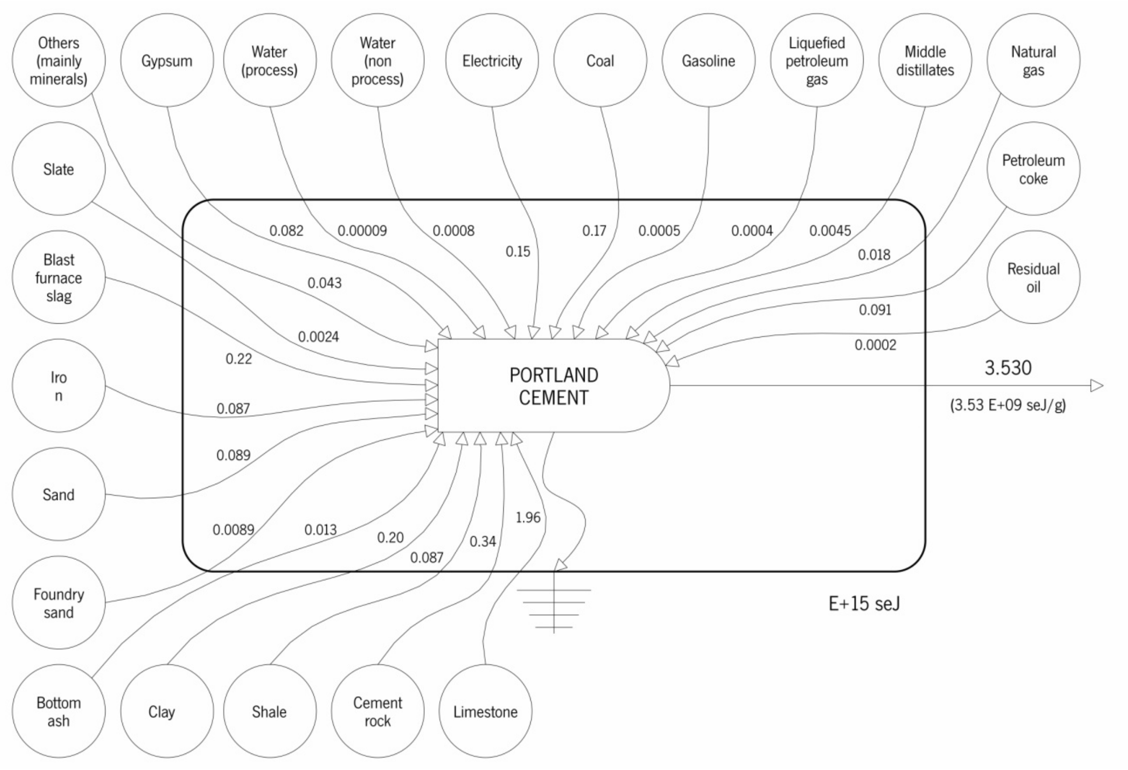


Figure 6.8. Emergy diagram of Portland cement (average system production without services).

6.6 *Emergy evaluation of concrete C20/25 (without services)*

Data for Emergy evaluation of Concrete C20/25 were collected from the survey for building construction operations published by Manso *et al.* (2005). Data on labour were not considered according with the system boundaries established for the Emergy evaluation procedures. However, mass waste in production of 1 ton of concrete was considered by Manso *et al.* (2005).

Table 6.9. Emergy analysis of concrete C20/25 (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Sand	g	6.26 E+05	2.24 E+09	1.40 E+15
2	Gravel	g	1.03 E+06	3.36 E+09	3.46 E+15
3	Aggregates	g	6.58 E+05	3.36 E+09	2.21 E+15
4	Portland cement	g	3.00 E+05	3.53 E+09	1.06 E+15
5	Water (potable)	g	3.16 E+05	7.96 E+07	2.52 E+13
Fuels and electricity					
6	Diesel	J	3.77 E+07	1.11 E+05	4.18 E+12
	Total EMERGY				8.16 E+15
	1 m^3 of concrete C20/25	g	2.40 E+06	3.40 E+09	8.16 E+15

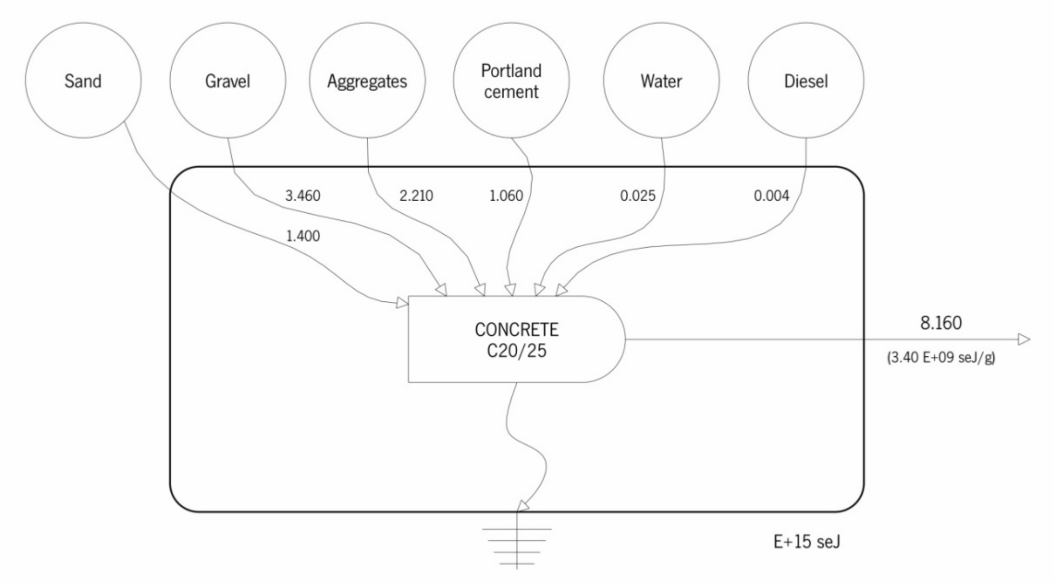


Figure 6.9. Emergy diagram of concrete C20/25 (without services).

6.7 *Emergy evaluation of mortars and plaster (without services)*

Data for Emergy evaluation of mortars and plaster were collected from the survey for building construction operations published by Manso *et al.* (2005). Data on labour were not considered according with the system boundaries considered for the Emergy evaluation procedures. However, mass waste in production of 1 ton of concrete was considered by Manso *et al.* (2005).

6.7.1 *Emergy evaluation of mortar (without services)*

Table 6.10. Emergy analysis of mortar (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Sand	g	1.70 E+06	2.24 E+09	3.82 E+15
2	Portland cement	g	2.98 E+05	3.53 E+09	1.05 E+15
3	Water (potable)	g	3.16 E+05	7.96 E+07	2.52 E+13
Fuels and electricity					
4	Diesel	J	3.77 E+07	1.11 E+05	4.18 E+12
	Total EMERGY				4.90 E+15
	1 m^3 of mortar	g	1.95 E+06	2.51 E+09	4.90 E+15

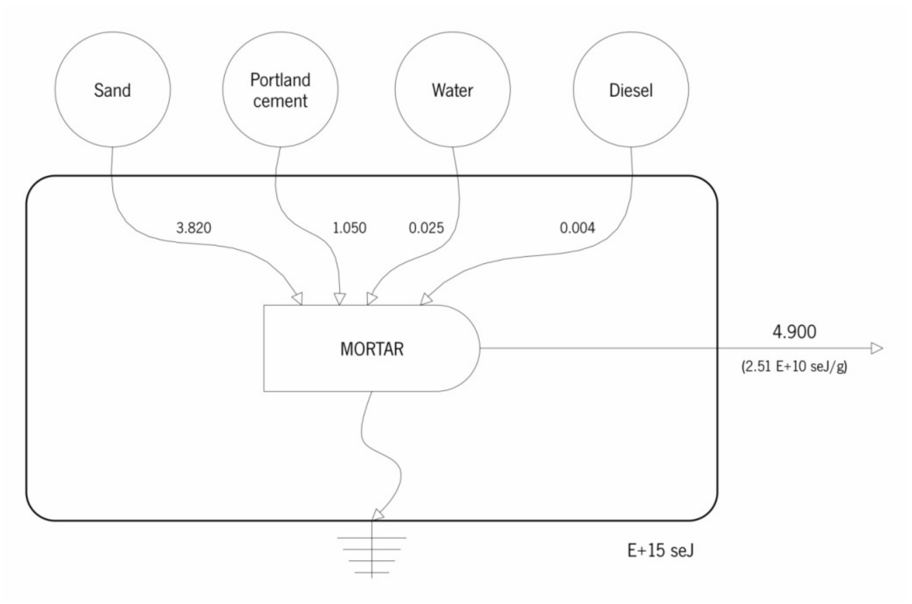


Figure 6.10. Emergy diagram of mortar (without services).

6.7.2 *Emergy evaluation of rendering mortar (without services)*

Table 6.11.Emergy analysis of rendering mortar (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Sand	g	2.40 E+04	2.24 E+09	5.38 E+13
2	Lime	g	4.20 E+03	1.68 E+09	7.06 E+12
3	Portland cement	g	4.20 E+05	3.53 E+09	1.48 E+13
4	Water	g	7.00 E+03	7.96 E+07	5.57 E+11
Fuels and electricity					
5	Diesel	J	3.77 E+07	1.11 E+05	4.18 E+12
	Total EMERGY				8.04 E+13
	1 m^2 of rendering mortar (2 cm thickness)	g	3.50 E+04	2.30 E+09	8.04 E+13

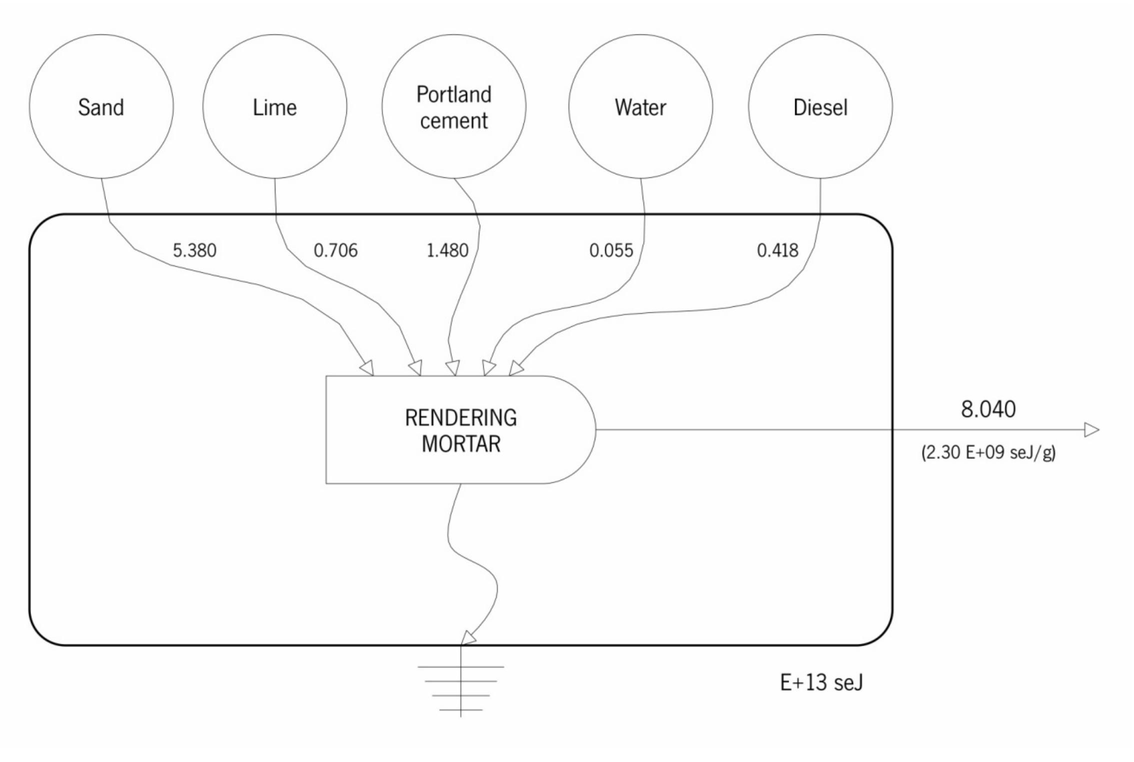


Figure 6.11. Emergy diagram of rendering mortar (without services).

6.7.3 *Emergy evaluation of finishing plaster (without services)*

Table 6.12. Emergy analysis of finishing plaster (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Lime	g	1.75 E+03	1.68 E+09	2.94 E+12
2	Gypsum	g	9.00 E+02	1.68 E+09	1.51 E+12
3	Water	g	6.00 E+03	7.96 E+07	4.78 E+11
	Total EMERGY				4.93 E+12
	1 m^2 of finishing plaster (3 mm thickness)	g	3.00 E+03	1.64 E+09	4.93 E+12

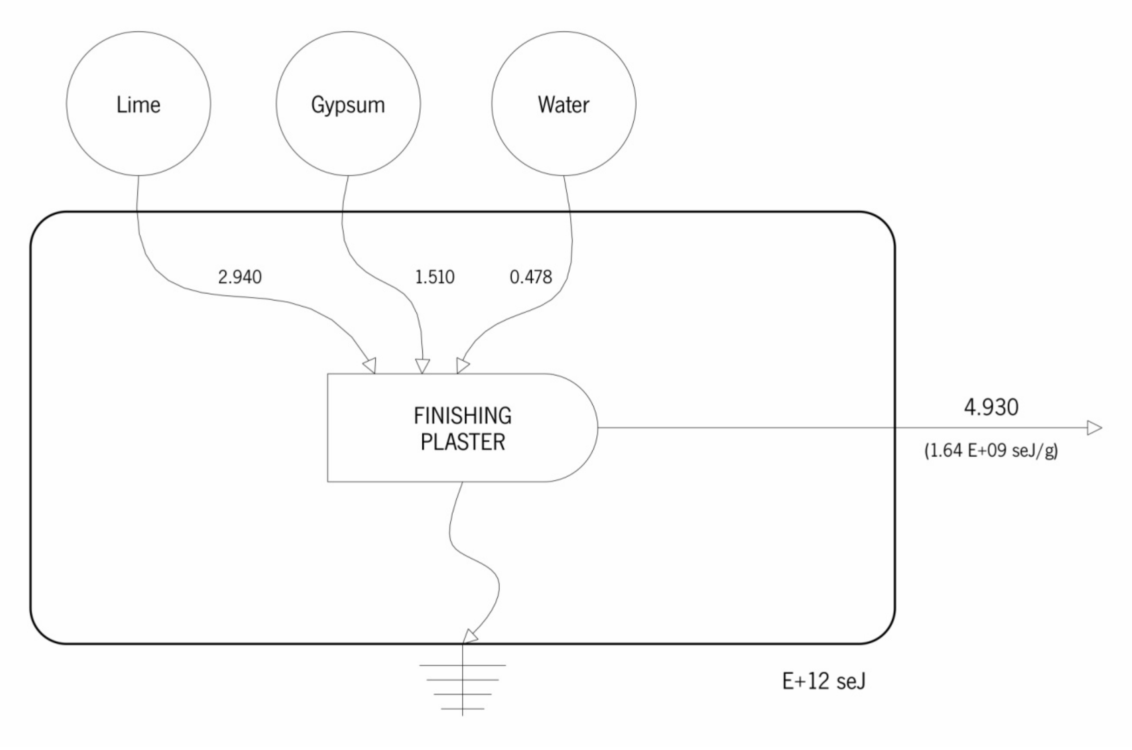


Figure 6.12. Emergy diagram of finishing plaster (without services).

6.8 *Emergy evaluation of finished painting (without services)*

Data for Emergy evaluation of painting were collected from the survey for building construction operations published by Manso *et al.* (2005).

Data on labour were not considered according with the system boundaries considered for the Emergy evaluation procedures.

Table 6.13. Emergy analysis of finished painting (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Paint (finishing)	g	2.74 E+02	3.11 E+09	8.52 E+11
2	Paint (primary)	g	6.12 E+01	3.11 E+09	1.90 E+11
3	Water	g	1.00 E+03	7.96 E+07	7.96 E+10
	Total EMERGY				1.12 E+12
	1 m^2 of finished painting	g	3.35 E+02	3.35 E+09	4.93 E+12

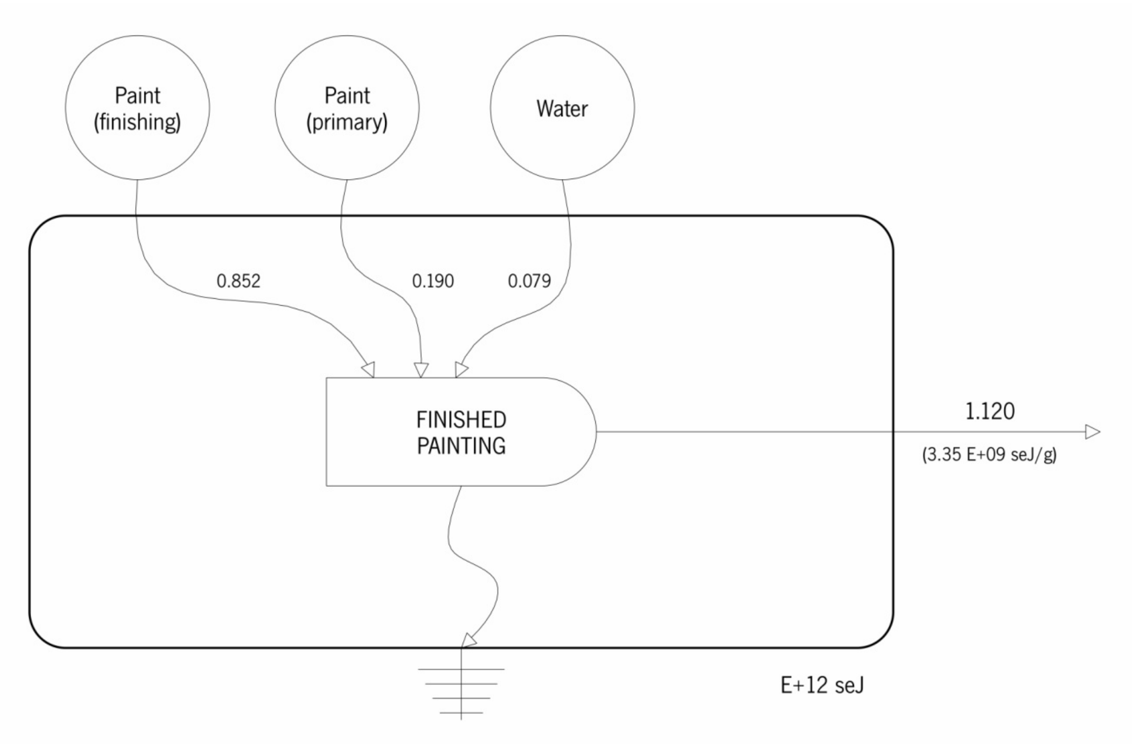


Figure 6.13. Emergy diagram of finished painting (without services).

6.9 *Emergy evaluation of OSB panel (without services)*

Data for the Emergy evaluation of Oriented Strand Board (OSB) panel were collected from the U.S. Life Cycle Inventory Database (http://www.nrel.gov/lci/).

The Life Cycle Inventory covers the following production stages:

(i) Reforesting;
(ii) Logs harvesting;
(iii) Sawing;
(iv) Panel manufacturing.

Table 6.14. Emergy analysis of OSB panel (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Harvested logs	g	8.56 E+03	6.79 E+08	5.31 E+12
2	Bark	g	3.08 E+013	6.79 E+08	2.09 E+08
3	PF resin	g	1.96 E+02	6.38 E+08	1.25 E+11
4	MDIA resin	g	3.77 E+01	6.38 E+08	2.41 E+10
5	Slack wax	g	8.92 E+01	6.38 E+08	5.69 E+10
6	Water	g	1.58 E+04	1.12 E+06	1.76 E+10
Fuels and electricity					
7	Electricity	J	8.15 E+06	2.92 E+05	2.38 E+12
8	Natural gas	J	1.60 E+07	8.06 E+04	1.29 E+12
9	Diesel	J	2.15 E+06	1.11 E+05	2.39 E+11
10	Distillate fuel oil	J	6.46 E+05	1.11 E+05	7.16 E+10
11	Liquefied petroleum gas (LPG)	J	6.93 E+05	1.11 E+05	8.15 E+10
12	Gasoline	J	1.55 E+05	1.11 E+05	1.72 E+10
13	Biomass	J	7.89 E+07	5.86 E+04	4.62 E+12
	Total EMERGY				1.00 E+13
	1 m^2 of OSB panel (0.95 cm thickness)	g	5.23 E+03	1.92 E+09	1.00 E+13

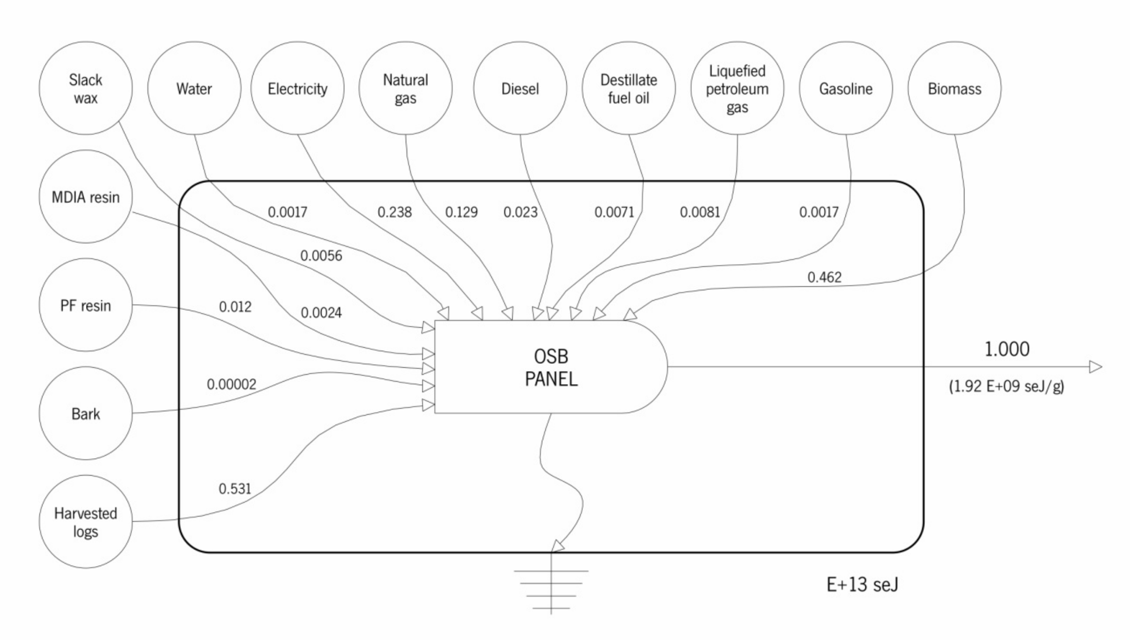


Figure 6.14. Emergy diagram of OSB panel (without services).

6.10 *Emergy evaluation of Thermoformed EPS (without services)*

Data for the Emergy evaluation of Expandable Polystyrene (EPS) were collected from the Life Cycle Assessment of plastics developed by Boustead (1999) for the Association of Plastics Manufacturers in Europe.

Life Cycle Inventory covers all the following production phases:

(i) Crude oil and natural gas production;
(ii) Benzene and ethylene processing;
(iii) Styrene polymerisation;
(iv) Expansion and thermoforming of Polystyrene.

Data on fuel oils and natural gas includes the material inputs for the cracking of ethylene from natural gas and naphtha, and for the reforming of benzene from naphtha.

Table 6.15.Emergy analysis of Thermoformed EPS (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Air	g	86.000	1.12 E+06	9.59 E+07
2	Bauxite	g	1.200	1.44 E+09	1.72 E+09
3	Bentonite	g	0.180	1.68 E+09	3.02 E+08
4	Calcium sulphate	g	0.018	1.68 E+09	3.02 E+07
5	Clay	g	3.800	3.36 E+09	1.28 E+10
6	Dolomite	g	0.014	1.68 E+09	2.35 E+07
7	Ferromanganese	g	0.001	1.68 E+09	1.68 E+06
8	Fluorspar	g	0.013	1.68 E+09	2.18 E+07
9	Gravel	g	0.004	2.24 E+09	8.96 E+06
10	Iron	g	1.200	4.45 E+09	5.34 E+09
11	Lead	g	0.004	1.68 E+09	6.72 E+06
12	Limestone	g	3.100	1.68 E+09	5.21 E+09
13	Nitrogen	g	32.000	7.04 E+09	2.25 E+11
14	Olivine	g	0.011	1.68 E+09	1.85 E+07
15	Oxygen	g	0.070	8.67 E+07	6.07 E+06
16	Phosphate	g	0.001	6.55 E+09	6.55 E+06
17	Potassium chloride	g	0.003	1.85 E+09	5.54 E+06
18	Sand	g	0.130	2.24 E+09	2.91 E+08

Table 6.15. – Continued.

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
19	Shale	g	0.049	1.68 E+09	8.23 E+07
20	Sodium chloride	g	21.000	1.68 E+09	3.53 E+10
21	Sulphur (bonded)	g	0.049	6.38 E+08	3.13 E+07
22	Sulphur (elemental)	g	0.130	6.38 E+08	8.30 E+07
23	Water (industry)	g	1.94 E+05	1.12 E+06	2.16 E+11
24	Water (potable)	g	1.86 E+03	7.51 E+07	6.46 E+11
Fuels and electricity					
25	Electricity	J	1.57 E+07	2.92 E+05	4.59 E+12
26	Oil fuels	J	3.69 E+07	1.11 E+05	4.10 E+12
27	Other fuels (mainly natural gas)	J	5.05 E+07	8.06 E+04	4.07 E+12
	Total EMERGY				1.39 E+13
	1 kg of Thermoformed EPS	g	1.00 E+03	1.39 E+10	1.39 E+13

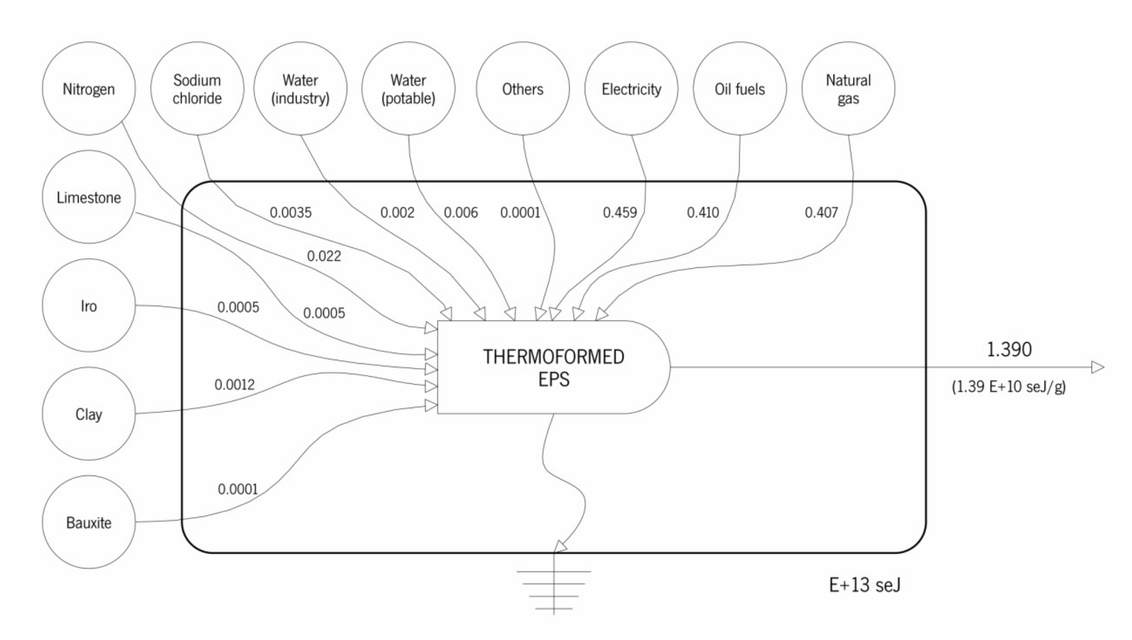


Figure 6.15. Emergy diagram of Thermoformed EPS (without services).

6.11 *Emergy evaluation of Aluminium extruded profiles (without services)*

Data for the Emergy evaluation of Aluminium extruded profiles were collected from the Life Cycle Inventory of the worldwide aluminium industry published by the International Aluminium Institute (IAI, 2000). A later report (IAI, 2003) was published using the data published on 2000.

The Life Cycle Inventory boundaries include the following phases of production:

(i) Bauxite mining;
(ii) Alumina refining;
(iii) Anode production;
(iv) Aluminium smelting (Primary aluminium);
(v) Primary ingot casting;
(vi) Recycling aluminium operations;
(vii) Aluminium extrusion, rolling, and shape casting.

For the Emergy evaluation of Aluminium extruded profiles was evaluated also the following production phases in order to get more accurate results:

(i) Alumina;
(ii) Anode carbon;
(iii) Primary aluminium;
(iv) Primary aluminium ingot;
(v) Recycled aluminium ingot.

For the evaluation of recycled aluminium ingot production, the Specific Emergy for recovered aluminium inputs (manufacturer scrap, post consumer scrap, and aluminium shreds) was considered as being the same as primary aluminium, according with the Emergy evaluation procedures.

The Specific Emergy value for recycled aluminium ingot was slightly higher than the Specific Emergy value for primary aluminium ingot. This increase in the Specific Emergy is due to

(i) Increased emergy inputs for collection, separation, shredding and decoating;
(ii) Decreased output of final material (1000 kg output for 1170 kg input).

6.11.1 *Emergy evaluation of Alumina (without services)*

Table 6.16.Emergy analysis of Alumina (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Bauxite	g	1.93 E+06	1.44 E+09	2.77 E+15
2	Caustic soda	g	7.50 E+04	1.68 E+09	1.26 E+14
3	Lime	g	4.80 E+04	1.68 E+09	8.06 E+13
4	Water (industry)	g	3.32 E+06	1.12 E+06	3.70 E+12
5	Sea water	g	3.46 E+06	1.81 E+05	6.28 E+11
Fuels and electricity					
6	Electricity	J	1.01 E+09	2.92 E+05	2.96 E+14
7	Fuel oil	J	5.86 E+09	1.11 E+05	6.49 E+14
8	Natural gas	J	5.94 E+09	8.06 E+04	4.79 E+14
9	Diesel	J	6.02 E+07	1.11 E+05	6.67 E+12
10	Coal	J	2.81 E+09	7.39 E+04	2.08 E+14
	Total EMERGY				4.62 E+15
	1 ton of Alumina	g	1.00 E+06	4.62 E+09	4.62 E+15

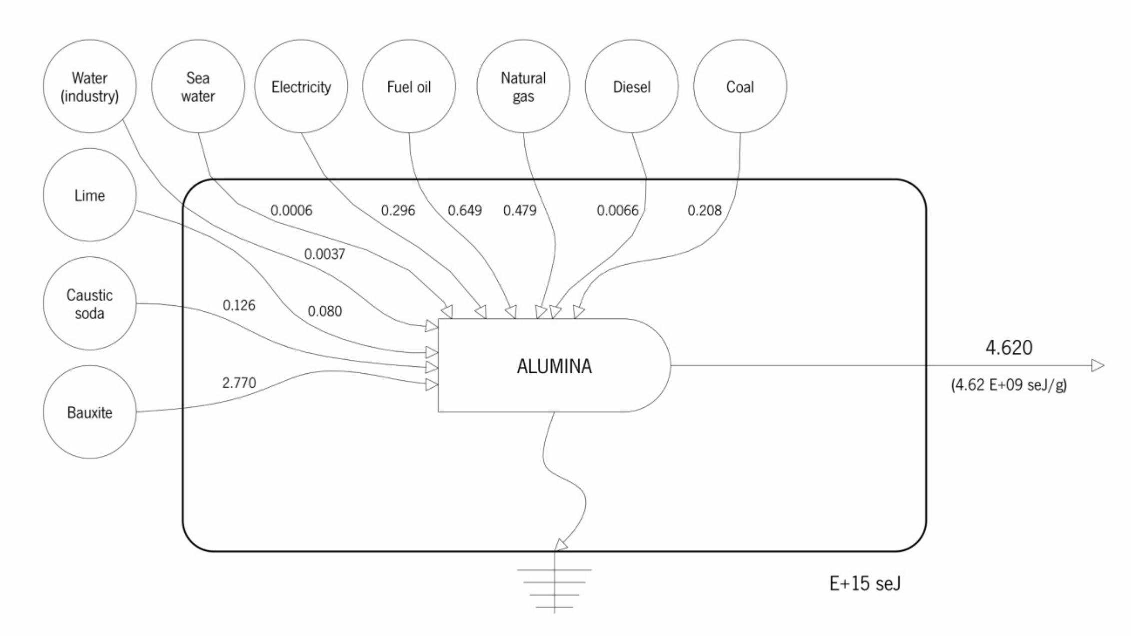


Figure 6.16. Emergy diagram of Alumina (without services).

6.11.2 *Emergy evaluation of Anode Carbon (without services)*

Table 6.17. Emergy analysis of Anode Carbon (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Coke	g	8.52 E+05	3.44 E+09	2.93 E+15
2	Pitch	g	2.35 E+05	1.68 E+09	3.95 E+14
3	Water (industry)	g	1.13 E+06	1.12 E+06	1.26 E+12
Fuels and electricity					
4	Electricity	J	1.13 E+09	2.92 E+05	3.29 E+14
5	Fuel oil	J	6.99 E+08	1.11 E+05	7.75 E+13
6	Natural gas	J	1.90 E+09	8.06 E+04	1.53 E+14
7	Diesel	J	1.83 E+08	1.11 E+05	2.03 E+13
	Total EMERGY				3.91 E+15
	1 ton of Anode Carbon	g	1.00 E+06	3.91 E+09	3.91 E+15

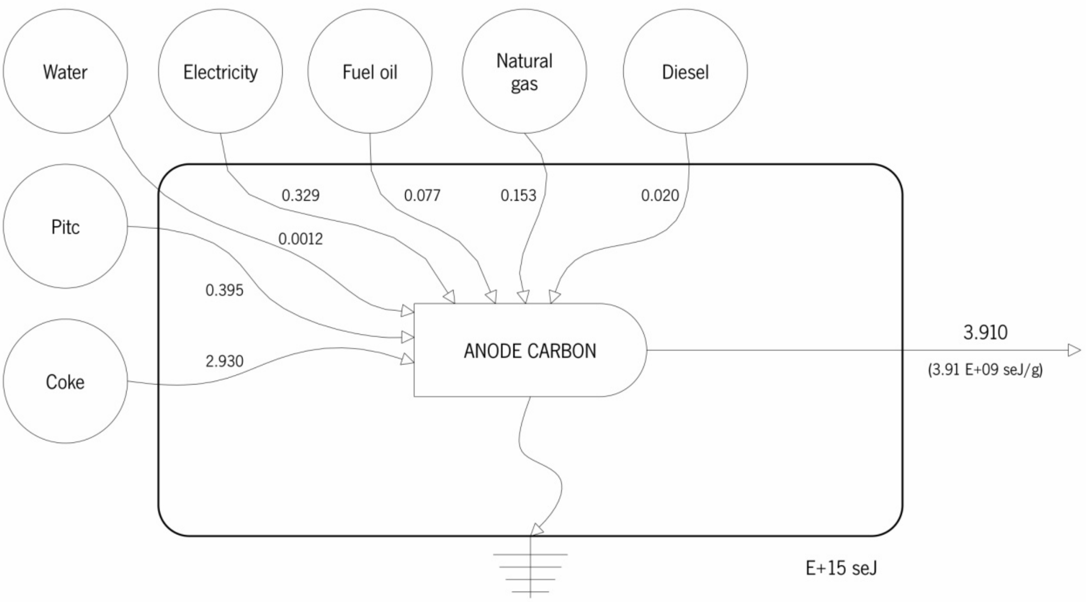


Figure 6.17. Emergy diagram of Anode Carbon (without services).

6.11.3 *Emergy evaluation of Aluminium primary metal (without services)*

Table 6.18. Emergy analysis of Aluminium primary metal (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Alumina	g	1.93 E+06	4.62 E+09	8.91 E+15
2	Anode carbon	g	4.43 E+05	3.92 E+09	1.74 E+15
3	Water (industry)	g	2.95 E+06	1.12 E+06	1.45 E+13
4	Sea water	g	2.14 E+07	1.81 E+05	5.12 E+12
Fuels and electricity					
5	Electricity	J	1.17 E+11	2.92 E+05	3.41 E+16
6	Fuel oil	J	6.99 E+08	1.11 E+05	7.75 E+13
7	Natural gas	J	1.90 E+09	8.06 E+04	1.53 E+14
8	Diesel	J	1.55 E+08	1.11 E+05	1.71 E+13
	Total EMERGY				4.50 E+16
	1 ton of Aluminum primary metal	g	1.00 E+06	4.50 E+10	4.50 E+16

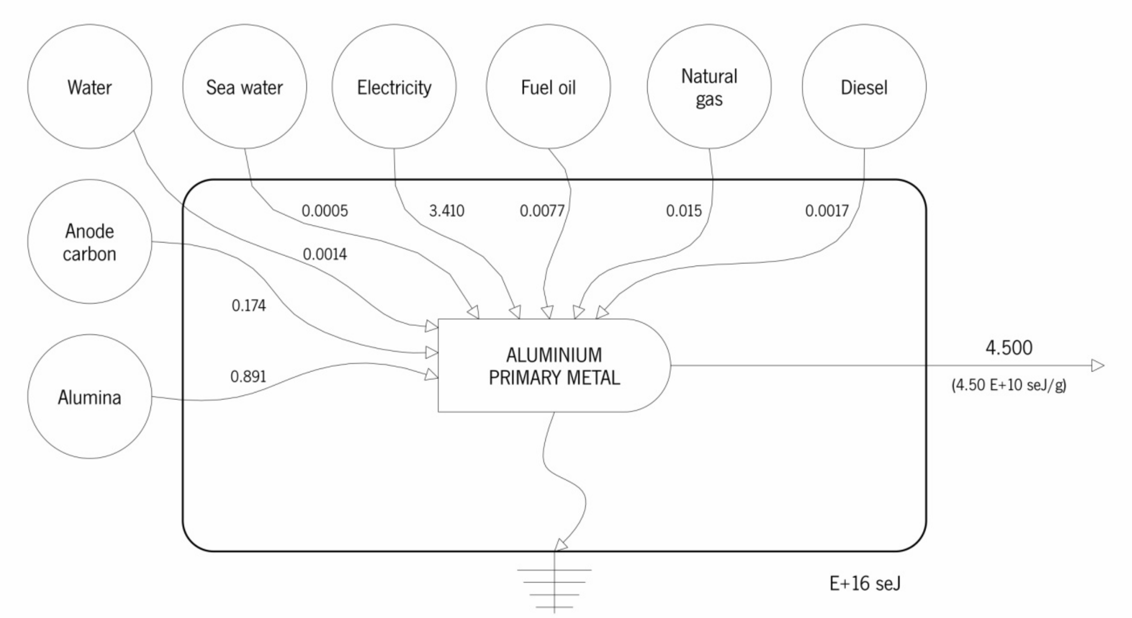


Figure 6.18. Emergy diagram of Aluminium primary metal (without services).

6.11.4 *Emergy evaluation of Aluminium primary ingot (without services)*

Table 6.19.Emergy analysis of Aluminium primary ingot (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Primary aluminium	g	1.00 E+06	4.50 E+10	4.50 E+16
2	Alloying additives	g	1.70 E+04	1.68 E+09	2.86 E+13
Fuels and electricity					
3	Electricity	J	1.55 E+09	2.92 E+05	4.51 E+14
4	Fuel oil	J	8.60 E+08	1.11 E+05	9.53 E+13
5	Natural gas	J	2.37 E+09	8.06 E+04	1.91 E+14
6	Diesel	J	8.00 E+06	1.11 E+05	8.87 E+11
7	Gasoline	J	3.21 E+06	1.11 E+05	3.56 E+11
8	Propane	J	2.30 E+07	8.06 E+04	1.85 E+12
	Total EMERGY				4.58 E+16
	1 Ton of Aluminium primary ingot	g	1.00 E+06	4.58 E+10	4.58 E+16

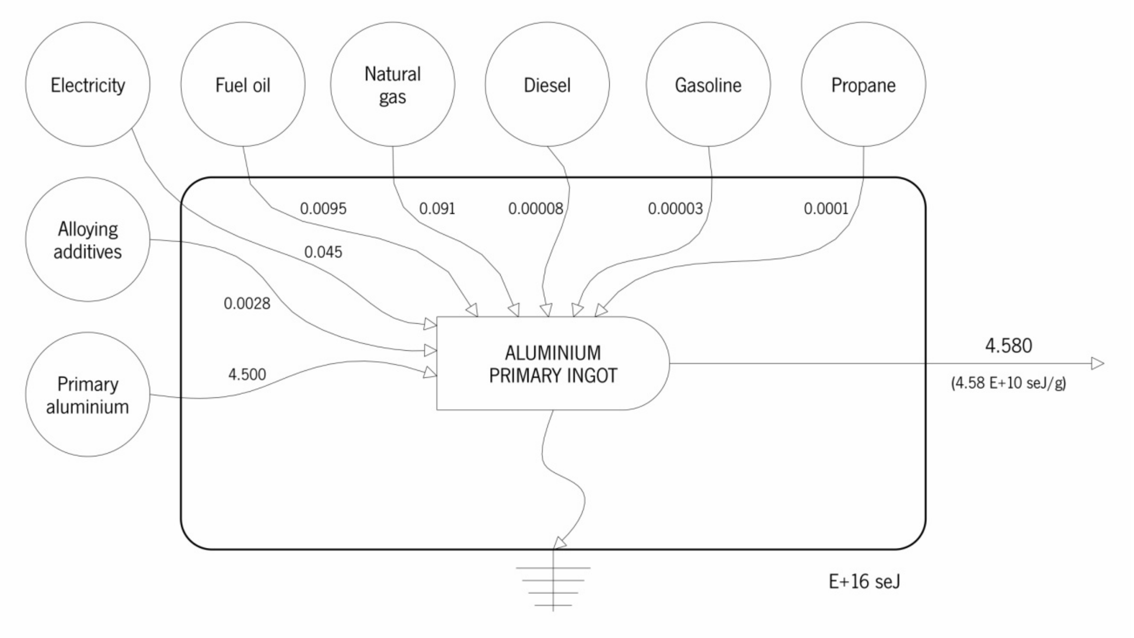


Figure 6.19. Emergy diagram of Aluminium primary ingot (without services).

6.11.5 *Emergy evaluation of Aluminium extruded profiles (without services)*

Table 6.20. Emergy analysis of Aluminium extruded profiles (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Primary aluminium ingot	g	1.44 E+06	4.58 E+10	6.60 E+16
Fuels and electricity					
2	Electricity	J	8.00 E+09	2.92 E+05	2.33 E+15
3	Fuel oil	J	2.06 E+08	1.11 E+05	2.28 E+13
4	Natural gas	J	2.68 E+09	8.06 E+04	2.16 E+14
5	Diesel	J	6.31 E+06	1.11 E+05	7.00 E+11
6	Gasoline	J	6.20 E+05	1.11 E+05	6.87 E+10
7	Propane	J	4.19 E+07	8.06 E+04	3.38 E+12
	Total EMERGY				6.85 E+16
	1 Ton of Aluminium extruded profiles	g	1.00 E+06	6.85 E+10	6.85 E+16

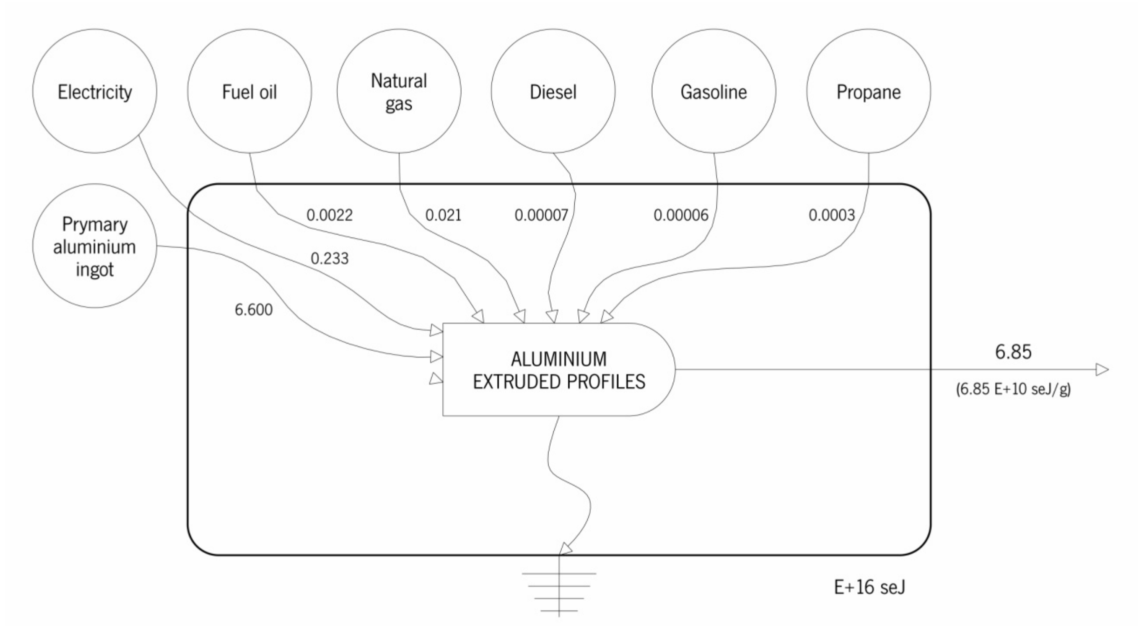


Figure 6.20. Emergy diagram of Aluminium extruded profiles (without services).

6.12 *Emergy evaluation of solid wood flooring (without services)*

Data for Emergy evaluation of solid wood flooring were collected from a Life Cycle Assessment of flooring materials published by Jonsson *et al.* (1996).

The Life Cycle Inventory includes the following phases of production: cultivation and felling; barking, sawing to the desired dimensions, and drying.

Table 6.21. Emergy analysis of solid wood flooring (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Raw materials					
1	Wood lumber	g	7.40 E+03	1.40 E+09	1.04 E+13
Fuels and electricity					
2	Electricity	J	8.37 E+06	2.92 E+05	2.44 E+12
3	Fossil fuels	J	5.39 E+06	1.11 E+05	5.98 E+11
4	Renewable fuels (wood biomass)	J	3.54 E+07	5.86 E+04	2.08 E+12
	Total EMERGY				1.55 E+13
	1 m^2 of solid wood flooring	g	7.40 E+03	2.09 E+09	1.55 E+13

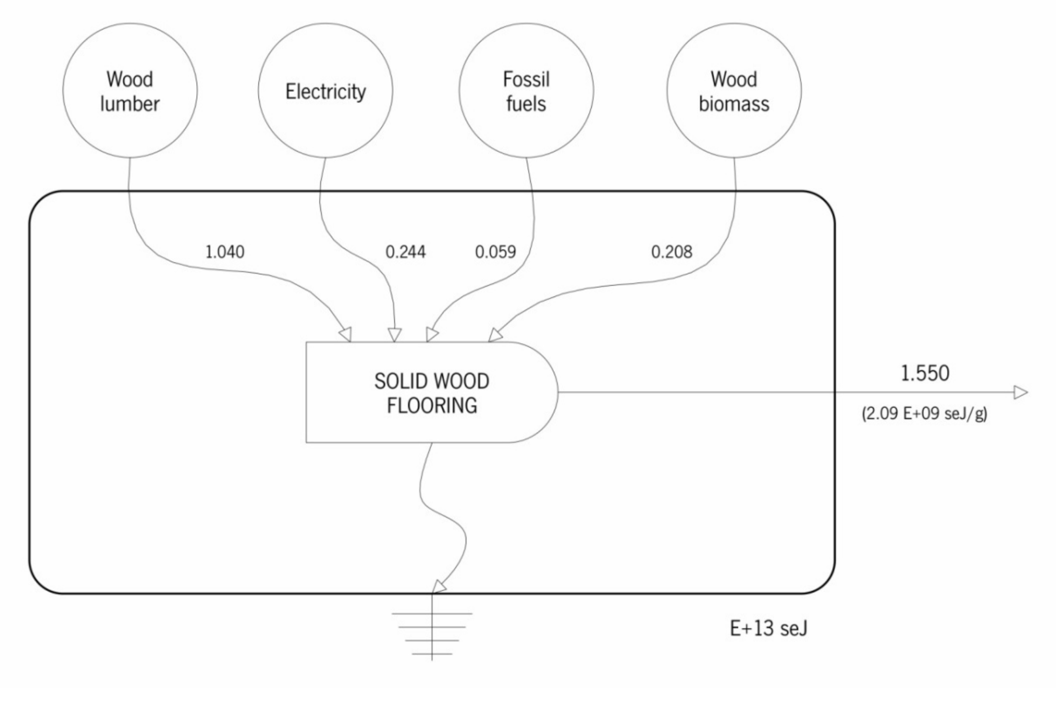


Figure 6.21. Emergy diagram of solid wood flooring (without services).

6.13 *Specific Emergy of building materials included in the proposed Model's database*

The database of the proposed Model includes values for Specific Emergy for most of common building materials.

The gathered values were obtained from this study and from literature, covering all the available data on Emergy and building materials.

For those materials which were found different Specific Emergy values, the criteria for selection were based on their accuracy and their actuality.

The overall data for Specific Emergy and Transformities for materials, products and energy sources included in the proposed Model's database are presented in Appendix C.

Table 6.22.Specific Emergy of building materials included in the proposed Model's database.

Item	Specific Emergy (seJ/g)	Reference sources
Aggregates	3.36 E+09	Odum (1996), p. 310, table C.4
Alumina (wo/s)	4.62 E+09	From this study (table 6.16)
Aluminium primary metal (wo/s)	4.50 E+10	From this study (table 6.18)
Aluminium primary ingot (wo/s)	4.58 E+10	From this study (table 6.19)
Aluminium extruded profiles (wo/s)	6.85 E+10	From this study (table 6.20)
Asphalt	7.69 E+08	Bjorklund *et al.* (2001), p. 299, table 1
Asphalt sheet	7.69 E+08	Assumed same as asphalt
Ceramic brick	4.23 E+09	Bjorklund *et al.* (2001), p. 299, table 1
Ceramic hollow brick	4.23 E+09	Assumed as ceramic brick
Ceramic tiles (wo/s)	3.32 E+09	From this study (table 6.3)
Concrete C20/25 (wo/s)	3.40 E+09	From this study (table 6.9)
Fiberglass	5.04 E+09	Ulgiati & Brown (2002), p. 341, table 1
Flat glass	7.96 E+09	Buranakarn (1998), p. 140, table A-1
Granite tiles (wo/s)	4.21 E+09	From this study (table 6.2)
Marble tiles	1.21 E+10	From this study (table 6.1)
Mortar (wo/s)	2.51 E+09	From this study (table 6.10)
Mortar (rendering) (wo/s)	2.30 E+09	From this study (table 6.11)
OSB Panel (wo/s)	1.92 E+09	From this study (table 6.14)
Paint	3.11 E+09	Brown & Ulgiati (2002), p. 327, table 2
Paint (finished)	3.35 E+09	From this study (table 6.13)
Plaster (wo/s)	1.64 E+09	From this study (table 6.12)

Table 6.22. – Continued.

Item	Specific Emergy (seJ/g)	Reference sources
Plasterboard (wo/s)	2.43 E+09	From this study (table 6.6)
Plasterboard (finished) (wo/s)	2.41 E+09	From this study (table 6.7)
Plastics (wo/s)	9.68 E+09	Buranakarn (1998), p. 143, table A-2
Plywood (wo/s)	2.74 E+09	Buranakarn (1998), p. 140, table A-1
Rock wool	3.09 E+09	Bjorklund et al. (2001), p. 299, table 1
Portland cement (wo/s)	3.53 E+09	From this study (table 6.8)
Steel (Mix wo/s)	5.31 E+09	Bargigli & Ulgiati (2003), p. 152, table 4
Thermoformed Expanded Polystyrene (EPS) (wo/s)	1.39 E+10	From this study (table 6.15)
Thermoformed Extruded Polystyrene (XPS) (wo/s)	1.39 E+10	Assumed same as thermoformed EPS
Varnish	3.11 E+09	Assumed same as paint
Wood lumbers (wo/s)	1.40 E+09	Buranakarn (1998), p. 143, table A-2
Wood plastic composites (wo/s)	9.42 E+09	Buranakarn (1998), p. 143, table A-2
Wood solid flooring (wo/s)	2.09 E+09	From this study (table 6.21)

CHAPTER 7

ASSESSMENT OF THE PROPOSED MODEL

One of the goals of the proposed model is that it can be applied both to building elements and to the whole buildings. Therefore, the case studies proposed here cover both levels of analysis. From these different approaches, different conclusions may be made concerning the outputs and behaviour of the proposed model.

For instance, the application of the proposed model at the building element level is simpler if the purpose is to analyse the behaviour of changes in the reference constraints such as End-of Life-Scenarios (ELS).

The application of the proposed model to a whole building system is more complex due to the larger number of types of materials involved and the relationships established between different building systems and subassemblies. At this level, the pattern of changes in the constraints is not so clear. However, differences in decision making regarding the main building system options become clearer, when comparing materials recovery effectiveness.

To evaluate the model at the building element level, a comparison between three different current building systems for interior walls is considered: brick masonry, plasterboard, and wood frame.

To evaluate the model at the whole building level it is proposed a small house dwelling. Three different structural systems are analysed: concrete frame, steel frame, and wood frame.

The data allocated to the case studies are in accordance with the collected data for the model’s database on what concerns density, specific Emergy, forecast service life, recovery rates, and end-of-life scenarios (see Chapters 3, 5 and 6).

Inventory of materials flows were performed by accounting all the inputs of materials necessary to build the dwellings or the building elements, using maps of quantities and quantity estimations from manufacturers.

Mass flows were estimated by multiplying materials input by their density (see footnotes to Emergy Evaluation of walls in Appendix D).

For the calculations, Forecast Service Life of materials and components were adjusted to express the Useful Life: Useful Life is considered as the time during which the material or component will be used, and therefore is a function of the Lifespan of the building, or a function of the precedence relationships with other materials. For example the Useful Life of a material with a Forecast Service Life greater than buildings Lifespan, is considered as equal to building Lifespan.

The allocation of End-of-Life Scenarios for materials for which Forecast Service Live is greater than Life Span, is assumed to be reclaimable for reuse, recycling, or energy recovery. Materials with Service Lives matching or lower than Lifespan are assumed to be reclaimed only for recycling or energy recovery purposes, according to the proposed Model principles.

Assumptions made for raw materials that will be substituted by recovered materials, are based on the best possible options regarding the following constraints: Useful Life, precedence relations, and disassembly properties.

According to the proposed Model's framework and principles (see Chapter 5), for each type of wall the following steps were performed:

(i) Inventory of mass flows for each material;
(ii) Allocation of data;
(iii) Analysis of building Configuration;
(iv) Analysis of End-of-Life Scenarios, and estimation of recovered mass according to the Recovery Rates;
(v) Emergy analysis;
(vi) Emergy analysis of materials for which recovered materials will be a substitute for;
(vii) Application of equations 1 to 5.

Infrastructures were not considered in the assessment, because their initial low Emergy and mass input would not influence the overall results. However, taking into account infrastructures would improve the accuracy of the Deconstruction Effectiveness results.

7.1 *Evaluation of the Model: application to interior walls*

The first application of the Model refers to one element of building. The element “interior wall” was chosen at this evaluation stage. The evaluation was performed by comparing three types of common wall in building systems:

(i) Wall W1: ceramic brick masonry;
(ii) Wall W2: plasterboard;
(iii) Wall W3: wood frame.

The Functional Unit (FU) is characterized by the following parameters:

(i) Dimensional reference: 1 square meter;
(ii) Life span: 50 years;
(iii) Acoustic insulation ($D_{n/w}$): 43 dB.

Variables regarding Service Life, Recovery Rates, recovery options, and substituted materials by recovered materials were defined according to the collected data, and the reference data established in Chapters 5 and 6. Furthermore, changes to ELS were made in order to test the model’s behaviour and accuracy.

Table 7.1. Assumptions made regarding Forecast Service Life for materials and components used in walls (see Chapter 5).

Wall	Component/service	Forecast Service life (years)
WALL W1 (Ceramic brick masonry)	Hollow bricks masonry	100
	Mortar	60
	Paint (Plaster finishing)	15
WALL W2 (Plasterboard)	Galvanized steel frame	75
	Insulation	>50
	Plasterboard	75
	Paint (Plaster finishing)	15
WALL W3 (Wood frame)	Wood frame	150
	Insulation	>50
	Plywood (panelling)	15
	Varnish (interior finishing)	15*

(*) Assumed to be the same as paint for internal finishing.

Table 7.2. Assumptions made regarding Estimated Recovery Rate (RR) for materials and components used in walls (see Chapter 5).

Wall	Material/Component	RR (%)
WALL W1	Bricks	90
	Plaster/Mortar	90
	Paint	0
WALL W2	Galvanized steel frame	97
	Mineral wool	93
	Plasterboard	95
	Paints	0
WALL W3	Wood frame	93
	Mineral wool	93
	Plywood (finishing)	93
	Varnish	0

7.1.1 *Interior wall W1: ceramic brick masonry*

The wall W1 is a traditional ceramic brick masonry wall, composed by the following building materials (see Figure 7.1):

(i) Ceramic hollow brick with 0.11 m thickness;
(ii) Rendering mortar with 0.02 m thickness;
(iii) Plaster with 0.003 m thickness;
(iv) Paint.

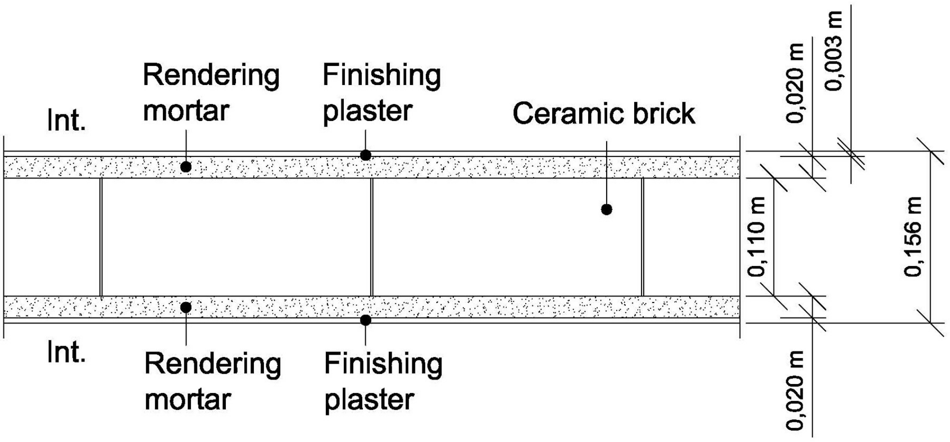


Figure 7.1. Horizontal cross section of wall W1: ceramic hollow brick.

(1) Analysis of building configuration and recovery scenarios for Wall W1

Adhesion bonding is the only type of connection employed in this construction system. Therefore, closed connections were considered as the precedence relationship between all materials (see Table 7.4).

Regarding materials recovery, it was assumed that only recycling scenarios were feasible, due to the kind of connections employed. The mixed waste produced from materials recovery was considered for downcycling.

Table 7.3. Inventory of materials flows for 1 m^2 of wall W1.

Note	Item	Data (units)	Unit	Reference
M-01: Ceramic brick masonry				
	Ceramic brick	16	Un	Manso *et al.* (2005)
	Mortar	0.016	m^3	Manso *et al.* (2005)
M-02: Plaster				
	Rendering mortar	0.04	m^3	This study
	Finishing plaster	0.01	m^3	This study
M-03: Paint				
	Paint (finishing)	0.40	l	Manso *et al.* (2005)
	Paint (primary)	0.12	l	Manso *et al.* (2005)
	Water	0.002	m^3	Manso *et al.* (2005)

Table 7.4. Analysis of building configuration of materials for 1 m^2 of wall W1.

Note	Item	Service Life (*) (yr)	Replacements	Mass (g)	Connections
M01 Ceramic hollow brick masonry		50	1	95,200	~~M02~~
M02 Plaster		50	1	80,000	~~M01~~ ~~M03~~
M03 Paint		15	4	670	~~M02~~

(*) Service life equals Lifespan of building element where forecast service life of materials is longer.

Where:

~~M_i~~ is for closed connections

M_i Is for open connection

Table 7.5. Analysis of end-of-life scenarios of materials for 1 m^2 of wall W1.

Note	Item	End-of-life scenarios for materials mass		
		Reuse (g)	Recycle (g)	No recovery (g)
M-01	Ceramic hollow brick masonry	0	85,680	9520
M-02	Plaster	0	72,000	8000
M-03	Paint	0	0	670

(2) Emergy evaluation of wall W1

Table 7.6. Emergy analysis of wall W1 (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
M-01: Ceramic hollow brick masonry					
1	Ceramic hollow brick	g	6.40 E+04	4.23 E+09	2.71 E+14
2	Mortar	g	3.12 E+04	2.51 E+09	7.83 E+13
					3.49 E+14
M-02: Plaster					
3	Rendering mortar	g	7.00 E+04	2.30 E+09	1.61 E+14
3	Finishing plaster	g	8.50 E+03	1.64 E+09	1.64 E+13
					1.77 E+14
M-03: Paint					
7	Paint (finishing)	g	5.48 E+02	3.11 E+09	1.70 E+12
8	Paint (primary)	g	1.22 E+02	3.11 E+09	3.81 E+11
9	Water (potable)	g	2.00 E+03	7.96 E+07	1.59 E+11
					2.09 E+12
	Total EMERGY initial input				5.29 E+14
	1 m^2 of interior ceramic brick masonry wall	g	1.76 E+05	3.01 E+09	5.29 E+14

Footnotes are given in Appendix D, Table D.1

(3) Emergy evaluation of best options for materials that will be substituted by recovered materials of wall W1

Table 7.7. Evaluation of best options for materials that will be substituted by recovered materials of wall W1.

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
M-01	Ceramic brick masonry				
MS-01	Granite	g	8.56 E+04	8.40 E+08	7.20 E+13
M-02	Plaster				
MS-02	Granite	g	7.20 E+04	8.40 E+08	6.05 E+13
M-03	Paint				
	Not substitute		0		0

See Appendix C for references on Unit Solar Emergy sources.

(4) Evaluation of deconstruction effectiveness of interior wall W1

Tables 7.8 to 7.10 present results of the application of DE equations to wall W1.

Table 7.8. Application of Equations 1 and 2 to materials composing wall W1.

Note	Item	Emergy (seJ)	Replacements	Equation 1 (seJ)
M-01	Ceramic brick masonry	3.49 E+14	1	3.49 E+14
M-02	Plaster	1.77 E+14	1	1.77 E+14
M-04	Paint	2.09 E+12	4	8.34 E+12
Equation 2: Total of Emergy of materials for wall W1 during Lifespan (seJ)				5.35 E+14

Table 7.9. Application of Equations 3 and 4 to best options for materials that will be substituted by recovered materials of wall W1.

Note	Mi	Note	MSi	Emergy of MSi (seJ)	Replacements	Equation 3 (seJ)
M01	Ceramic brick masonry	MS01	Aggregates	7.20 E+13	1	7.20 E+13
M02	Plaster	MS02	Aggregates	6.05 E+13	1	6.05 E+13
M03	Paint	MS03	None	0	4	0
Equation 4: Recovery Effectiveness of wall W1 (seJ)						1.32 E+14

Table 7.10. Application of Equation 5 to wall W1.

Recovery Effectiveness of W1 (seJ)	Emergy of W1 (seJ)	DE
1.32 E+14	5.35 E+14	0.25

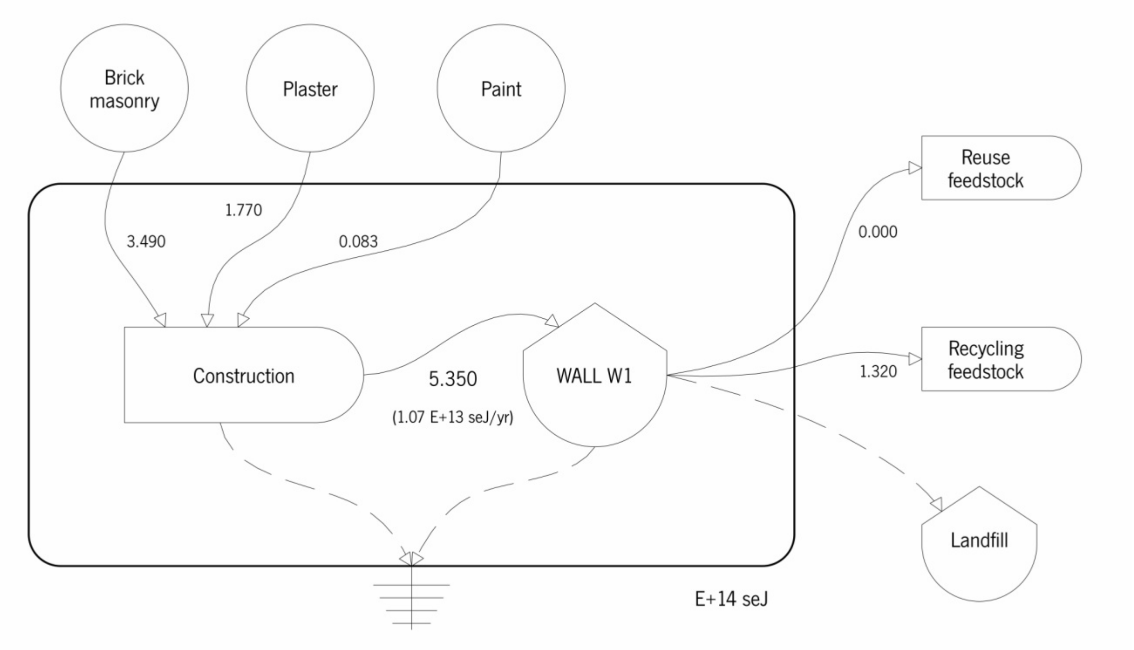


Figure 7.2. Emergy diagram of wall W1 (without services).

7.1.2 *Interior* wall W2*: plasterboard*

The wall W2 is a drywall constituted by using the following materials (see Figure 7.3):

(i) Galvanized steel frame;
(ii) Mineral wool medium density;
(iii) Plasterboard 0.013 m thickness (including finishing stucco);
(iv) Paint.

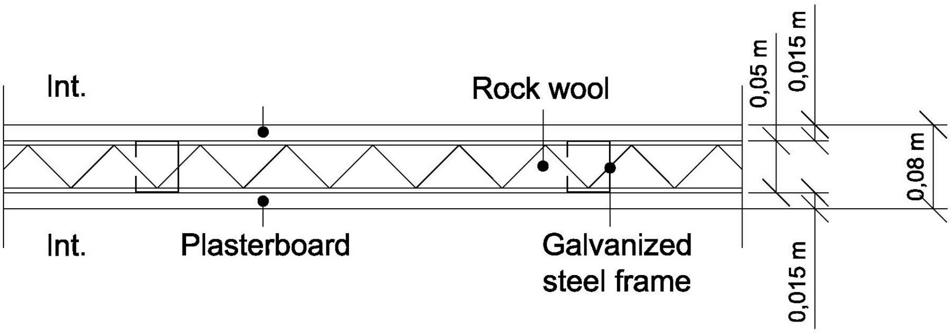


Figure 7.3. Horizontal cross section of wall W2: plasterboard.

(1) Analysis of building configuration and recovery scenarios for wall W2

Mechanical connections are the main type of connection employed in this construction system. Screwing is employed to connect the galvanized steel frame sections and the plasterboard panel to the steel frame. Mineral wool is fitted inside the panels to reduce acoustic bridges. Therefore, open connections were considered as the precedence relationship between all materials (see Table 7.12), with an exception for the finishing layer.

In materials recovery, and in spite of the disassemble connections employed, it was assumed that only recycling scenarios were really feasible, due to the kind of removal processes usually employed to remove plasterboard panels and the steel frame. However, easy separation of materials was considered as an advantage for recycling.

Table 7.11. Inventory of materials flows for 1 m^2 of wall W2.

Note	Item	Data (units)	Unit	Reference
M-01	Galvanized steel frame			
	Galvanized steel rail R48	0.90	m	Iberplaco (2004)
	Galvanized steel rail M46	3.00	m	Iberplaco (2004)
M-02	Mineral wool	0.042	m^3	This study
M-03	Plasterboard			
	Plasterboard panel	2	m^2	
	Gypsum	0.66	kg	Iberplaco (2004)
	Water	0.33	kg	Iberplaco (2004)
M-04	Paint			
	Paint (finishing)	0.40	l	Manso *et al.* (1997)
	Paint (primary)	0.12	l	Manso *et al.* (1997)
	Water	0.002	m^3	Manso *et al.* (1997)

Table 7.12. Analysis of building configuration of materials for 1 m^2 of wall W2.

Note	Item	Service Life (*) (yr)	Replacements	Mass (g)	Connections		
M01	Galvanized steel frame	50	1	1743	M02	M03	
M02	Mineral wool	50	1	1680	M01	M03	
M03	Plasterboard	50	1	21,060	M01	M03	~~M04~~
M04	Paint	15	4	670	~~M03~~		

(*) Service life equals Lifespan of building element where forecast service life of materials is longer.

Where:

~~M_i~~ is for closed connections

M_i Is for open connection

Table 7.13. Analysis of end-of-life scenarios of materials for 1 m^2 of wall W2.

Note	Item	End-of-life scenarios for materials mass		
		Reuse (g)	Recycle (g)	No recovery (g)
M-01	Galvanized steel frame	0	1691	52
M-02	Mineral wool	1562	0	118
M-03	Plasterboard	0	20,007	1053
M-04	Paint	0	0	670

(2) Emergy evaluation of wall W2

Table 7.14. Emergy analysis of wall W2 (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
M-01: Galvanized steel frame					
1	Galvanized steel rail R48	g	4.11 E+02	5.31 E+09	2.18 E+12
2	Galvanized steel rail M46	g	1.33 E+03	5.31 E+09	7.07 E+12
					9.26 E+12
M-02: Mineral wool					
3	Mineral wool	g	1.68 E+03	3.09 E+09	5.19 E+12
					5.19 E+12
M-03: Plasterboard					
4	Plasterboard panel	g	2.04 E+04	2.43 E+09	4.96 E+13
5	Gypsum	g	6.60 E+02	1.68 E+09	1.11 E+12
6	Water (potable)	g	3.30 E+02	7.96 E+07	2.63 E+10
					5.07 E+13
M-04: Paint					
7	Paint (finishing)	g	5.48 E+02	3.11 E+09	1.70 E+12
8	Paint (base)	g	1.22 E+02	3.11 E+09	3.81 E+11
9	Water (potable)	g	2.00 E+03	7.96 E+07	1.59 E+11
					2.24 E+12
	Total EMERGY initial input				6.74 E+13
	1 m^2 of interior plasterboard wall	g	2.52 E+04	2.68 E+09	6.74 E+13

Footnotes are given in Appendix D, Table D.2

(3) Emergy evaluation of best options for materials that will be substituted by recovered materials of wall W2

Table 7.15. Emergy evaluation of best options for materials that will be substituted by recovered materials of wall W2.

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
M-01	Galvanized steel frame				
MS-01	Pig iron	g	1,69 E+03	3.34 E+09	5.65 E+12
M-02	Mineral wool				
MS-02	Mineral wool	g	1.56 E+03	3.09 E+09	4.83 E+12
M-03	Plasterboard				
MS-03	Gypsum	g	2.00 E+04	1.68 E+09	3.36 E+13
M-04	Paint				
	Not substitute		0		0

See Appendix C for references on Unit Solar Emergy sources.

(4) Evaluation of deconstruction effectiveness of interior wall W2: plasterboard

Tables 7.16 to 7.18 present results of the application of DE equations to wall W2.

Table 7.16. Application of Equations 1 and 2 to materials composing Wall W2.

Note	Item	Emergy (seJ)	Replacements	Equation 1 (seJ)
M-01	Galvanized steel frame	9.26 E+12	1	9.26 E+12
M-02	Mineral wool	5.19 E+12	1	5.19 E+12
M-03	Plasterboard	5.07 E+13	1	5.70 E+13
M-04	Paint	2.24 E+12	4	8.98 E+12
Equation 2: Total of Emergy of materials for wall W2 during Lifespan(seJ)				7.41 E+13

Table 7.17. Application of Equations 3 and 4 to best options for materials that will be substituted by recovered materials of Wall W2.

Note	Mi	Note	MSi	Emergy of MSi (seJ)	Replacements	Equation 3 (seJ/yr)
M01	Galvanized steel frame	MS01	Pig iron	5.65 E+12	1	5.65 E+12
M02	Mineral wool	MS02	Mineral wool	4.83 E+12	1	4.83 E+12
M03	Plasterboard	MS03	Gypsum	3.36 E+13	1	3.36 E+13
M04	Paint	MS04	None	0	4	0
Equation 4: Recovery Effectiveness of wall W2 (seJ)						4.41 E+13

Table 7.18. Application of Equation 5 to wall W2.

Recovery Effectiveness of W2 (seJ)	Emergy of W2 (seJ)	DE
4.41 E+13	7.41 E+13	0.59

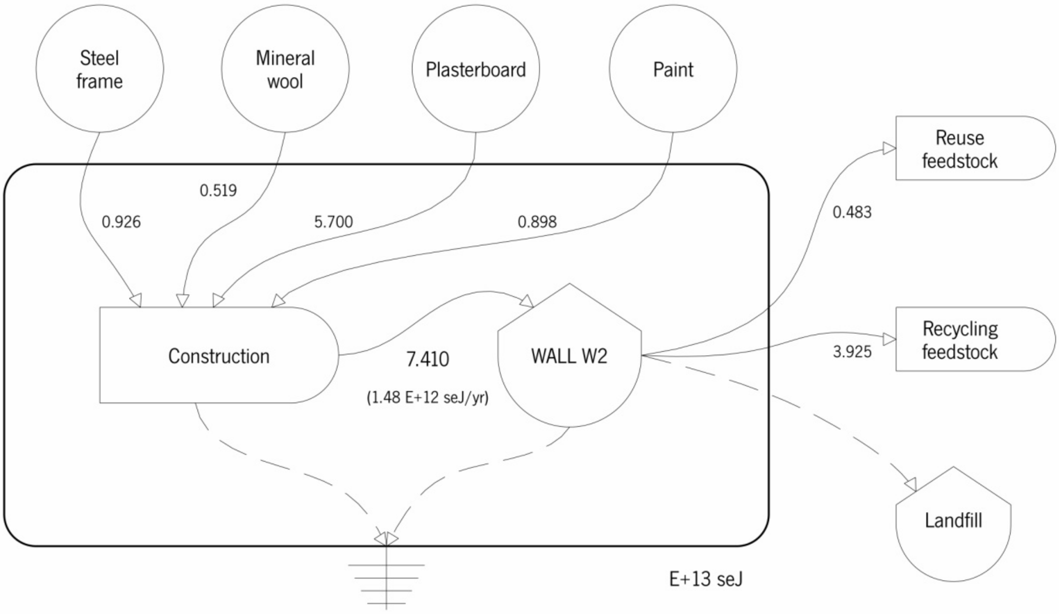


Figure 7.4. Emergy diagram of wall W2 (without services).

7.1.3 *Interior wall W3: wood frame*

The wall W3 is a light wood frame wall, composed by the following materials (see Figure 7.3):

- (i) Wood frame (Pine);
- (ii) Mineral wool medium density;
- (iii) Plywood 0.015 m thickness;
- (iv) Varnish.

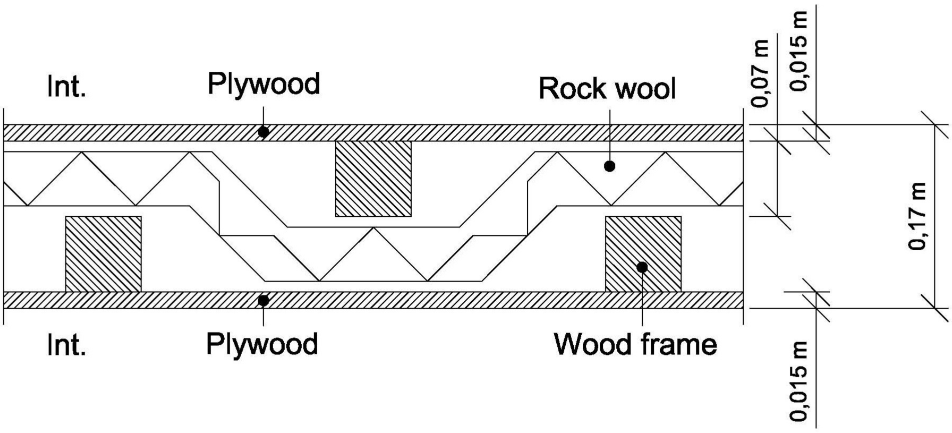


Figure 7.5. Horizontal cross section of wall W3: wood frame.

(1) Analysis of building configuration and recovery scenarios for wall W3

The connections employed in this construction system are mechanical ones. Screwing or nailing is employed to connect the wood frame sections and the plywood panel to the wood frame. Mineral wool is between the wood frame. Therefore, open connections were considered as the precedence relationship between all materials (see Table 7.20), excepting the finishing layer.

Regarding materials recovery, as considered for Wall W2, it was assumed that only recycling scenarios are feasible, due to the kind of removal processes usually employed. However, easy separation of materials was considered as an advantage for recycling.

Table 7.19. Inventory of materials flows for 1 m^2 of wall W3.

Note	Item	Data (units)	Unit	Reference
M-01: Wood frame (pine)		0.029	m^3	This study
M-02: Mineral wool		0.072	m^3	This study
M-03: Plywood (15 mm thickness)		2	m^2	This study
M-04: Varnish		0.40	l	This study

Table 7.20. Analysis of building configuration of materials for 1m^2 of wall W3.

Note	Item	Service Life (*) (yr)	Replacements	Mass (g)	Connections		
M01	Wood frame (pine)	50	1	17,658	M02	M03	
M02	Mineral wool	50	1	2890	M01	M03	
M03	Plywood (15 mm thickness)	15	4	13,800	M01	M03	~~M04~~
M04	Varnish	15	4	424	~~M03~~		

(*) Service life equals Lifespan of building element where forecast service life of materials is longer.

Where:

~~M$_i$~~ is for closed connections

M$_i$ Is for open connection

Table 7.21. Analysis of end-of-life scenarios of 1 m^2 of wall W3.

Note	Item	End-of-life scenarios for materials mass		
		Reuse (g)	Recycle (g)	No recovery (g)
M-01	Wood frame (pine)	0	16,422	1236
M-02	Mineral wool	2687	0	202
M-03	Plywood (15 mm thickness)	0	12,834	966
M-04	Varnish	0	0	424

(2) Emergy evaluation of Wall W3

Table 7.22. Emergy analysis of wall W3 (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
M-01: Wood frame (pine)					
1	Wood (pine)	g	1.77 E+04	1.40 E+09	2.47 E+13
					2.47 E+13
M-02: Mineral wool					
2	Mineral wool	g	2.89 E+03	3.09 E+09	8.93 E+12
					8.93 E+12
M-03: Plywood					
3	Plywood (15 mm thickness)	g	1.38 E+04	2.74 E+09	3.78 E+13
					3.78 E+13
M-04: Varnish					
4	Varnish	g	4.24 E+02	3.11 E+09	1.32 E+12
					1.32 E+12
	Total EMERGY initial input				7.28 E+13
	1 m^2 of interior wood frame wall	g	3.48 E+04	2.09 E+09	6.30 E+13

Footnotes are given in Appendix D, Table D.3

(3) Emergy evaluation of best options for materials that will be substituted by recovered materials of Wall W3

Table 7.23. Emergy evaluation of best options for materials that will be substituted by recovered materials of wall W3.

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
M-01	Wood frame (pine)				
MS-01	Wood logs	g	1,64 E+04	6.79 E+08	1.12 E+13
M-02	Mineral wool				
MS-02	Mineral wool	g	2.68 E+03	3.09 E+09	8.30 E+12
M-03	Plywood				
MS-03	Wood logs	g	1.28 E+04	6.79 E+08	8.71 E+12
M-04	Varnish				
	Not substitute		0		0

See Appendix C for references on Unit Solar Emergy sources.

(4) Evaluation of deconstruction effectiveness of interior wall W3: wood frame

Tables 7.24 to 7.26 present results of the application of DE equations to wall W3.

Table 7.24. Application of Equations 1 and 2 to materials composing wall W3.

Note	Item	Emergy (seJ)	Replacements	Equation 1 (seJ)
M-01	Wood frame (pine)	2.47 E+13	1	2.47 E+13
M-02	Mineral wool	8.39 E+12	1	8.39 E+12
M-03	Plywood	3.78 E+13	4	1.51 E+14
M-04	Varnish	1.32 E+12	4	1.32 E+12
Equation 2: Total of Emergy of materials for wall W3 during Lifespan(seJ)				1.90 E+14

Table 7.25. Application of Equations 3 and 4 to best options for materials that will be substituted by recovered materials of wall W3.

Note	Mi	Note	MSi	Emergy of MSi (seJ)	Replacements	Equation 3 (seJcp)
M01	Wood frame (pine)	MS01	Wood logs	1.12 E+13	1	1.12 E+13
M02	Mineral wool	MS02	Mineral wool	8.30 E+12	1	8.30 E+12
M03	Plywood	MS03	Wood logs	8.71 E+12	4	3.49 E+13
M04	Varnish	MS04	None	0	4	0
Equation 4: Recovery Effectiveness of wall W3 (seJ)						5.43 E+13

Table 7.26. Application of Equation 5 to wall W3.

Recovery Effectiveness of W3 (seJ)	Emergy of W3 (seJ)	DE
5.43 E+13	1.90 E+14	0.29

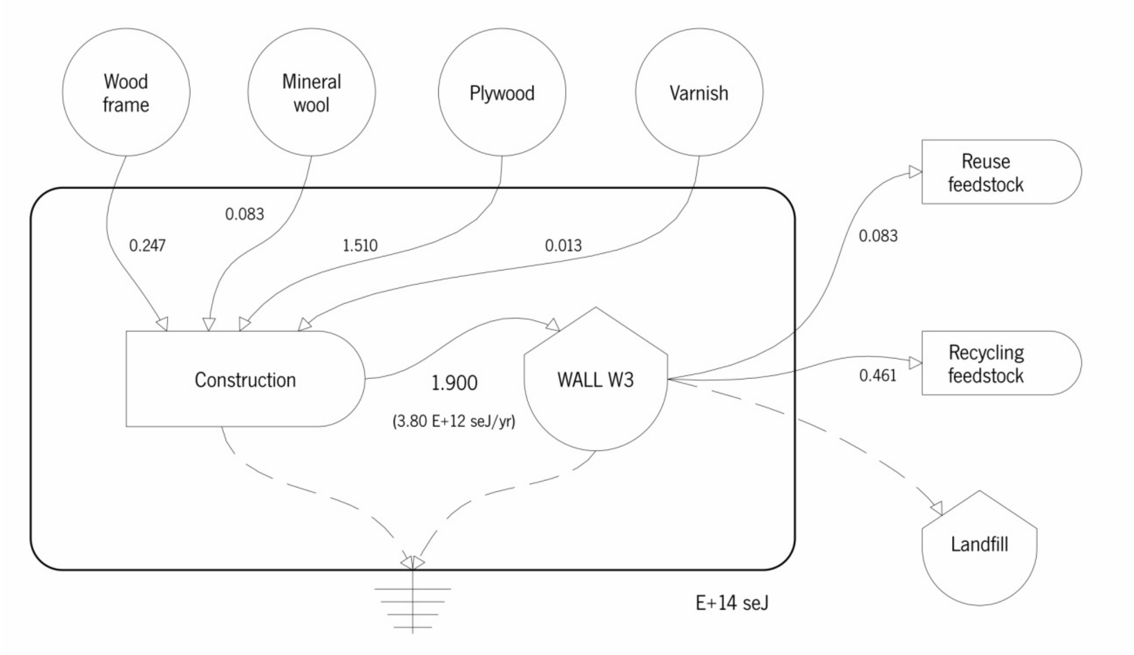


Figure 7.6. Emergy diagram of wall W3 (without services).

7.1.4 *Comparison of interior walls evaluation*

The Deconstruction Effectiveness for the three interior are compared in the following comparison tables and graphs (see Table 7.27 and Figure 7.7 to Figure 7.10).

Table 7.27. Synthesis of Deconstruction Effectiveness (DE) evaluation

	Wall W1	Wall W2	Wall W3
DE	0.25	0.59	0.29

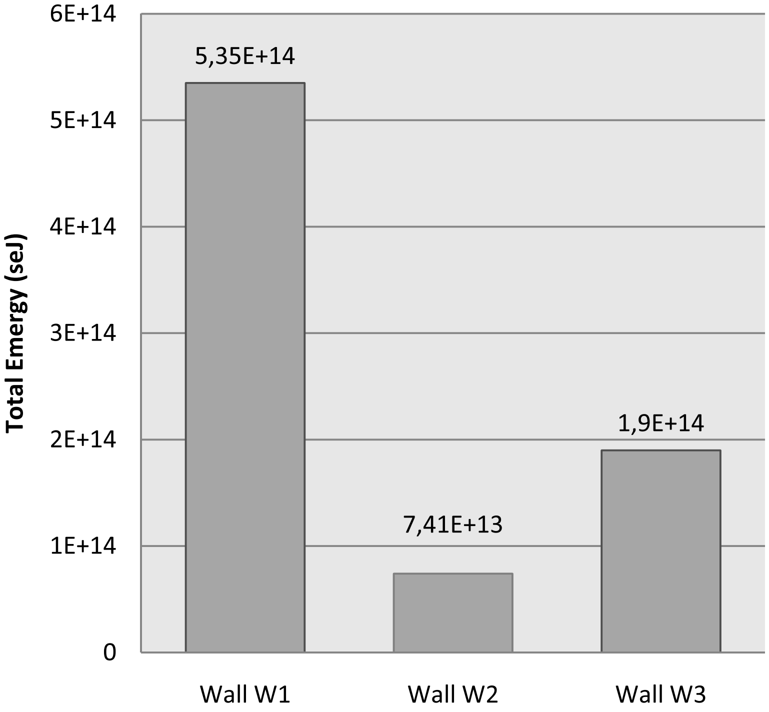


Figure 7.7. Comparison between walls W1, W2 and W3: total Emergy input during Lifespan.

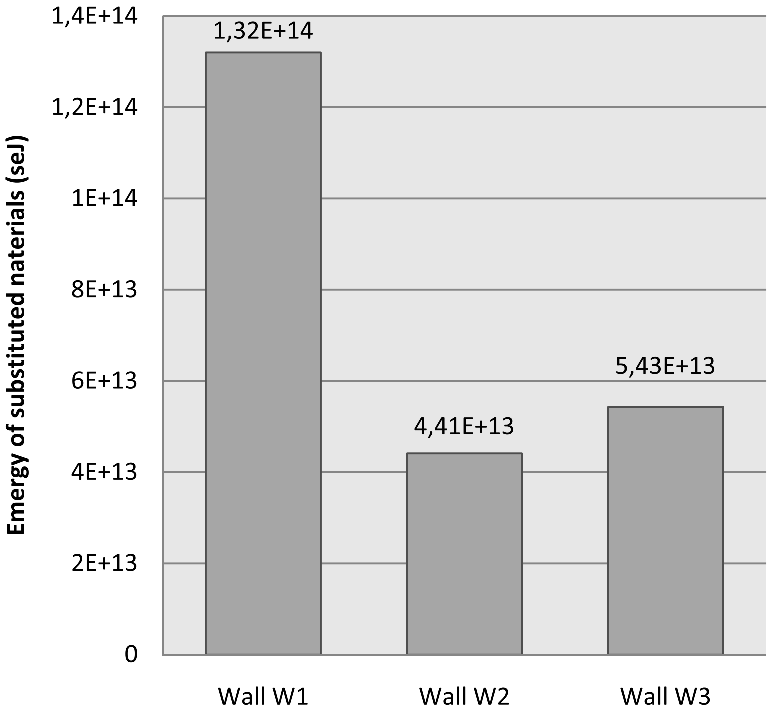


Figure 7.8. Comparison between walls W1, W2 and W3: total Emergy of substituted materials during Lifespan.

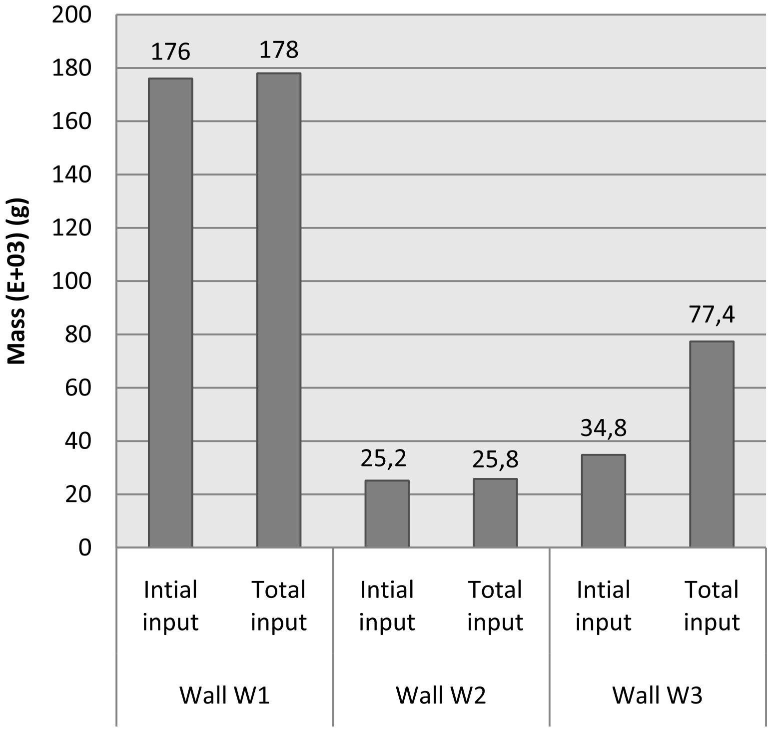


Figure 7.9. Comparison between walls W1, W2 and W3: total mass input during Lifespan.

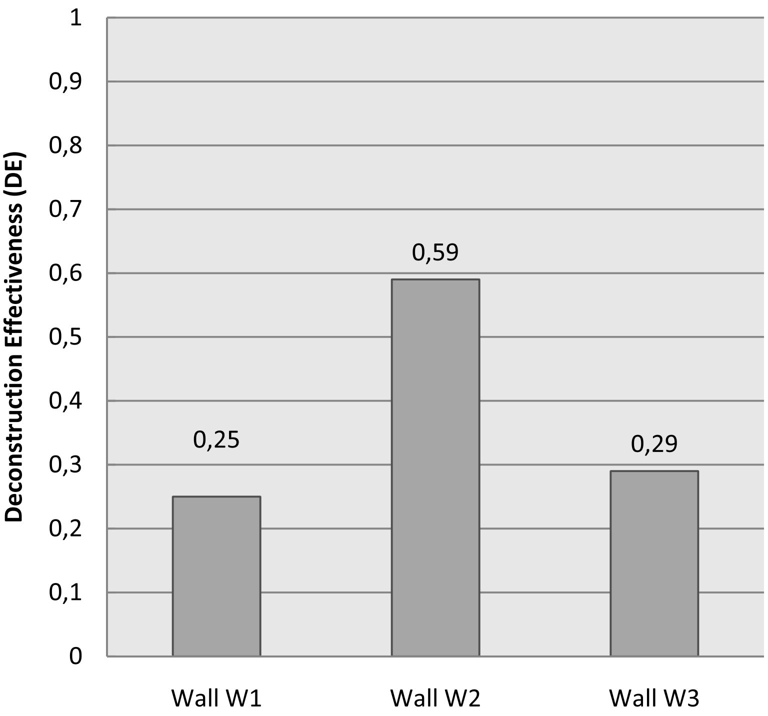


Figure 7.10. Comparison between walls W1, W2 and W3: Deconstruction Effectiveness.

Wall W1 does not exhibit disassembly properties, and the reclaimed materials are not separable. In spite of the highest total Emergy input during the lifespan (see Figure 7.7), mainly due to the high amount of inputed mass, the recycling of the reclaimed materials in a downcycling process, such as raw materials for aggregates production, does not benefit the overall environmental performance of the wall.

Wall W2 that is based on a disassemblable system, and composed by materials with higher specific Emergy, has the higher Deconstruction Effectiveness. The higher Emergy per mass of galvanized steel benefits the best options for the raw materials that are substituted as expected from the Emergy principles. Wall W2 has the lowest Emergy and mass input during the wall lifespan (see Figure 7.7 and Figure 7.9), enhancing wall W2 as the technological system with better environmental net benefit.

Wall W3, despite being also based on a disassemble system does not have a high deconstruction effectiveness due to the low specific Emergy of the employed materials, and the low specific Emergy of the substituted raw materials. Due to the low durability of the plywood, the total mass input during Lifespan increases 122 %, from 34.8 E+03 g to 77.4 E+03 g (see Figure 7.9). Furthermore, wall W3 benefits from the reuse end-of-life scenario for mineral wool, otherwise the Deconstruction Effectiveness would be much lower.

7.1.5 *Behaviour of the proposed Model for different end-of-life scenarios (ELS)*

End-of-life scenario is a variable of the proposed Model and it is considered according to the type of connections employed and the most feasible technology for material recovery. Thus, alternatives to end-of-life scenarios were performed for wall W2, and wall W3, simulating changes on connections types in order to produce changes on the allocated End-of-Life Scenarios.

Wall W1 was not considered in the analysis, because it was not possible to consider alternatives to the kind of connections employed.

(1) Wall W2

Alternatives to End-of-Life Scenarios for wall W2 were considered to simulate reuse and disposal alternatives for plasterboard and a recycling scenario for mineral wool (see Table 7.28):

(i) ELS2: partial reuse and partial recycling for plasterboard;
(ii) ELS3: total disposal of plasterboard;
(iii) ELS4: recycling of mineral wool and total disposal of plasterboard.

Table 7.28. Wall W2: alternatives for different End-of-Life Scenarios (ELS).

Note	Material	ELS 1 (initial)	ELS 2	ELS 3	ELS 4
M-01	Galvanized steel frame	Recycling	Recycling	Recycling	Recycling
M-02	Mineral wool	Reuse	Reuse	Reuse	Recycling
M-03	Plasterboard	Recycling	Reuse/recycling	Disposal	Disposal
M-04	paint	Disposal	Disposal	Disposal	Disposal
Deconstruction Effectiveness (DE)		0.59	0.69	0.14	0.11

Application of equations are given in Appendix E

As expected, Deconstruction Effectiveness index (DE) decreases according to the decrease of recovered mass as shown for ELS3 and ELS4. Due to its high specific Emergy, disposal of plasterboard reduces initial DE index from 0.59 to 0.14 in ELS3 and to 0.11 in ELS4.

Furthermore, an increase in recovered plasterboard for reuse increases the overall performance of the final index. Regarding the initial scenario ELS 1, the scenario ELS 2 improves the DE index from 0.59 to 0.69 by considering the partial reuse of plasterboard. Unfortunately, this scenario was not considered as the most feasible due to the existing constraints to plasterboard removal, such as hidden screws.

The overall results show the importance of recovering the materials used in Wall W2, regarding the environmental net benefit of keeping those materials in the supply loop chain of construction.

(2) Wall W3

Changes in screwed connections to nailed connections were considered for Wall W3 assembly. As connection type influences the end of- life scenarios, other recovery paths were considered for wall W3, simulating combustion and disposal alternatives for plywood, and a recycling scenario for mineral wool (see Table 7.29):

(i) ELS2: combustion of plywood;
(ii) ELS3: combustion both of plywood and wood frame;
(iii) ELS4: total wood combustion and recycling of mineral wool.

Table 7.29. Wall W3: alternatives for different End-of-Life Scenarios (ELS).

Note	Material	ELS 1 (initial)	ELS 2	ELS 3	ELS 4
M-01	Wood frame (pine)	Recycling	Recycling	Combustion	Combustion
M-02	Mineral wool	Reuse	Reuse	Reuse	Recycling
M-03	Plywood	Recycling	Combustion	Combustion	Disposal
M-04	Varnish	Disposal	Disposal	Disposal	Disposal
Deconstruction Effectiveness (DE)		0.29	0.18	0.14	0.05

Application of equations are given in Appendix E.

As expected, Deconstruction Effectiveness index (DE) decreases according to the lower quality of recovered materials. With less mass being recovered for recycling and reuse, DE decreases for ELS2, ELS3 and ELS4. As most of the components of wall W3 are produced from renewal resources, they have a low specific Emergy, i.e. a high environmental net benefit from recovering wood based materials is not achieved, when compared to wall W1 and wall W2.

7.1.6 *Discussion*

The application of the proposed model stressed the environmental value and the quality of the materials employed, as in case of wall W2. Materials with higher Emergy per mass exhibits higher durability and better alternatives for end-of-life scenarios. Furthermore, as these materials have higher environmental value their reclamation is of utmost importance in order to reduce the environmental load of resources consumption in construction. This is the case of metals for example.

Changes to forecast service life and recovery rates were not considered in the simulated changes, as those values are considered to be the properties inherent to the materials and not variables used in the proposed Model. However, from the calculation procedures, it is possible to state that DE would decrease with lower material recovery rates.

Regarding useful life, the proposed approach enhances durability and hierarchical relationships between materials. A decrease of the useful life of a material decreases the final DE index due to increase of the Emergy flow per year would increase.

For example, a decrease in useful life of plywood from 15 years to 10 years decreases DE of wall W3 from 0.29 to 0.27. However, if the useful life of plywood is considered to be 25 years instead of 15 years, DE of wall W3 would increase from 0.29 to 0.32, and Emergy flow per year decrease from 3.80 E+12 to 2.29 E+12. These predictions of the proposed Model demonstrates that durability affects the Deconstruction Effectiveness index clearly, which is in accordance with the resources conservation principle.

From the analysis of these case studies, is possible to state that the results for the several kinds of interior walls are coherent according with the theoretical approach in which the principles of the Deconstruction Effectiveness index are grounded.

7.2 *Case study 2: 3 types of building systems*

The second stage of the model's evaluation is it application to a whole building in order to evaluate the model's possibility regarding more complex structures.

Therefore, the proposed Model was applied to three kinds of a small house dwelling. The technological system employed distinguishes the three case studies under assessment:

(i) Building B1: load bearing concrete structure;
(ii) Building B2: load bearing steel frame structure;
(iii) Building B3: load bearing timber frame structure.

For each building, materials applied in building subsystems, such as walls, floors, and roofs, are coherent with the structural system considered. For example:

(i) In the concrete structural house, brick masonry walls are considered;
(ii) In the steel frame house, plasterboard walls are considered;
(iii) In the timber frame house, wood frame walls are considered.

The functional unit considered has the following dimensions parameters:

(i) Plan dimensional reference: a grid of 0.60 x 0.60 m;
(ii) Plan structural dimensional reference: a length of 6.00 m
(iii) Structural height: 3.12 m.

Concrete foundations were considered for the three alternatives studied.

Variables regarding service life, recovery rates, recovery options, and substituted materials by recovered materials were defined according to the reference data of the proposed Model (see Table 7.30 and Table 7.31).

Changes in internal wall solution for building B1 and building B3 were considered to verify the improvement of DE in accordance with the feedback improvement step of the proposed Model

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Table 7.30. Assumptions made regarding Service Life for materials and components used for building B1 (see Chapter 5).

Component/service	Forecast Service life (years)
Aluminium (window framing)	30
Asphalt sheet (not exposed)	50
Ceramic hollow brick	100
Ceramic tiles (walls)	30
Concrete	>100
EPS (Cladding out insulation)	50
EPS (Insulation not exposed)	50
Flat glass	60
Granite tiles (flooring)	100
Gravel	>50
Marble tiles (flooring)	100
Mineral wool	>50
Mortar (not exposed)	60
Mortar (rendering)/Plaster	60
OSB panel	85
Paint (mortar exterior)	5
Paint (plaster interior)	15
Paint (steel exterior)	15
Plasterboard	75
Plastic lumber (flooring)	50
Plywood (interior)	15
PVC (roofing sheets)	20
Steel (cladding)	60
Steel (wall framing)	75
Steel (reinforcing)	>50
Steel (structural profiles)	200
Varnish (exterior finishing)	3
Varnish (interior finishing and floor)	15
Wood (columns and beams)	60-150
Wood (framing)	75
Wood (interior elements and doors)	30
Wood (siding panels)	40
Wood floor (solid wood)	30
Wood window frame	40
XPS (insulation not exposed)	50
Zinc sheet	>50

Table 7.31. Assumptions made regarding Estimated Recovery Rate (RR) for materials and components used for Building B1 (see Chapter 5).

Component/service	Recovery Rate (%)
Aluminium	95
Asphalt sheet (not exposed)	0
Ceramic hollow brick	90
Ceramic tiles (walls)	90
Concrete	93
EPS (Cladding out insulation)	0
EPS (Insulation not exposed)	0
Flat glass	93
Granite tiles (flooring)	90
Gravel	90
Marble tiles (flooring)	90
Mineral wool	93
Mortar (not exposed)	90
Mortar (rendering)/Plaster	90
OSB panel	93
Paint (mortar exterior)	0
Paint (plaster interior)	0
Paint (steel exterior)	0
Plasterboard	95
Plastic lumber (flooring)	93
Plywood	93
PVC (roofing sheets)	0
Steel (cladding)	97
Steel (wall framing)	97
Steel (reinforcing)	93
Steel (structural profiles)	97
Steel sheet	93
Varnish (exterior finishing)	0
Varnish (interior finishing and floor)	0
Wood (columns and beams)	93
Wood (framing)	93
Wood (interior elements and doors)	93
Wood floor (solid wood)	93
XPS (insulation not exposed)	0
Zinc sheet	95

7.2.1 *Building B1: concrete structural system*

Building B1 is composed of a load bearing structure made of reinforced concrete, with the following set of building materials employed as described in Table 7.32:

(i) External and internal walls: hollow brick masonry;
(ii) Thermal insulation: outside application of EPS in external walls and XPS in the floor and roof;
(iii) Roof: gravel and zinc sheet;
(iv) External walls and ceilings finishing: mortar and paint;
(v) External pavements: granite tiles;
(vi) Internal pavements: wood floor and marble tiles;
(vii) Internal walls finishing: mortar, plaster, and ceramic tiles;
(viii) Internal ceilings finishing: mortar, plaster, and paint;
(ix) External doors and windows: aluminium profiles, and double flat glass;
(x) Internal doors: wood.

Figure 7.11. Building B1: 3D general view.

Figure 7.12. Building B1: 3D North view.

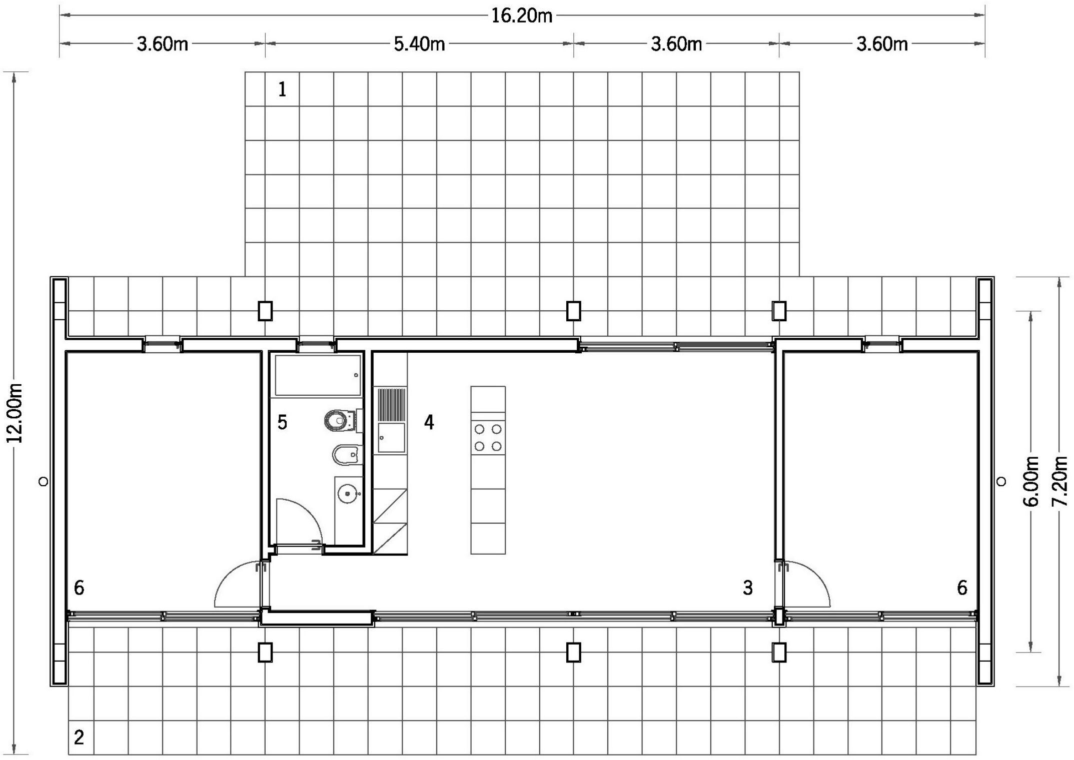

Figure 7.13. Building B1: plan
(1) Terrace, 2) Balcony, 3) Living room, 4) Kitchen, 5) Bathroom, 6) Bedroom.

Figure 7.14. Building B1: 3D cross section.

The connections employed in building B1 are predominantly adhesion bonding ones. Due to the technological system employed, cement based materials for bonding is employed, i.e. cement mortar, in most of the materials assembly, such as bricks, stone and ceramic tiles, insulation, and finishing of walls and ceilings.

Therefore, closed connections are considered as the precedence relationship for most of the materials employed in building B1 (see Appendix F).

Concerning materials recovery, it was assumed in most cases that recycling scenarios were feasible, due to the kind of connections employed. The mixed waste (e.g. concrete, mortar, and bricks) produced from materials recovery was considered for downcycling purposes. Steel recovered from structural concrete was considered for recycling purposes by magnetic separation from mixed waste. Aluminium sections from doors and windows, as well as wood based materials, were considered predominantly for recycling.

Calculations are here summarized and detailed calculations are presented in Appendix F (building characterisation), Appendix I (Emergy evaluation), Appendix J (Emergy evalution of best options for materials that will be substituted by recovered materials), and Appendix K (DE calculations).

Table 7.32. Building B1: synthesis of mass inventory.

Note	Item	Mass (g)
S01: FOUNDATIONS		
S01-E01	Square base	2.63 E+07
S01-E02	Columns	2.48 E+06
Total S01		2.88 E+07
S02: STRUCTURAL FRAME		
S02-E01	Columns	5.10 E+06
S02-E02	Beams ground floor	1.75 E+07
S02-E03	Beams roof	1.18 E+07
S02-E04	Slab ground floor	8.33 E+07
S02-E05	Slab roof	6.73 E+07
Total S02		1.85 E+08
S03: FAÇADES AND ROOFS		
S03-E01	External walls	2.18 E+07
S03-E02	Doors	1.33 E+06
S03-E03	Windows	2.20 E+05
S03-E04	Roof	1.37 E+07
Total S03		3.70 E+07
S04: FLOORS		
S04-E01	External floor	1.20 E+07
S04-E02	Interior floor	1.14 E+07
Total S04		2.35 E+07
S05: INTERIOR PARTITION		
S05-E01	Interior walls	9.09 E+06
S05-E02	Doors	1.14 E+05
Total S05		9.21E+06
S06: CEILINGS		
S06-E01	External ceilings	1.21 E+06
S06-E02	Interior ceilings	2.52 E+06
Total S06		3.72 E+06
Total mass input (g)		**2.88 E+08**

A detailed inventory is given in Appendix F.

Table 7.33.Building B1: synthesis of Emergy analysis of material flows (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Total Emergy initial input		g	2.88 E+08		9.73 E+17
Initial Emergy per gram (seJ/g)				3.37 E+09	

Detailed calculations are given in Appendix I.

Application of the equations and detailed calculations of Deconstruction Effectiveness for Building B1 are presented in Appendix K.

Table 7.34. Building B1: Deconstruction Effectiveness.

Recovery Effectiveness of B1 (seJ)	Emergy of B1 (seJ)	DE
3.05 E+17	1.00 E+18	0.303

7.2.2 *Building B2: steel structural system*

Building B2 is composed of a load bearing structure made of steel sections, with the following set of building materials employed as described in Table 7.35:

(i) External and internal walls: steel framing, and OSB panels;
(ii) Thermal insulation: mineral wool in external walls, XPS in the floor, and structural EPS thermal insulation panel in the external walls and roof;
(iii) Roof: PVC sheet, and steel sheet;
(iv) External walls and ceilings finishing: steel cladding;
(v) External pavements: wood plastic composite deck;
(vi) Internal pavements: wood floor and marble tiles;
(vii) Internal walls finishing: plasterboard, and paint;
(viii) Internal ceilings finishing: plasterboard, and paint;
(ix) External doors and windows: aluminium profiles, and double flat glass;
(x) Internal doors: wood.

Figure 7.15. Building B2: 3D general view.

Figure 7.16. Building B2: 3D North view.

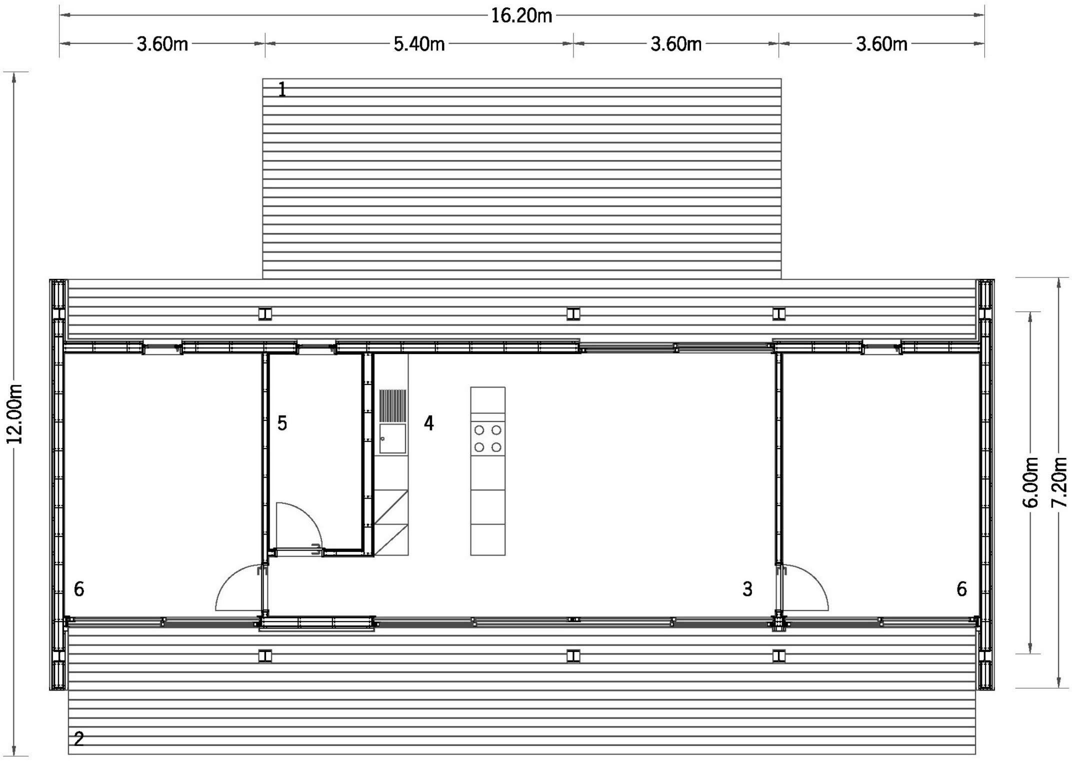

Figure 7.17. Building B2: plan
1) Terrace, 2) Balcony, 3) Living room, 4) Kitchen, 5) Bathroom, 6) Bedroom.

Figure 7.18. Building B2: 3D cross section.

The connections employed in building B2 are predominantly mechanical ones. Due to the technological system employed, screwing and nailing is the most employed method.

Therefore, open connections were considered as the predominant precedence relationship for most of the materials employed in building B2 (see Appendix G).

Regarding materials recovery, it was assumed in most cases that reuse recycling scenarios were feasible, due to the kind of connections employed. Structural steel sections were considered as being screwed, and therefore reuse of such elements was considered as the most feasible recovery scenario. Internal walls and ceilings materials, such as steel and plasterboard, were considered for recycling as it was considered in the Wall W2 case study. Aluminium sections from doors and windows, as well as wood based materials, were considered predominantly for recycling. Other mixed waste from materials recovery, such as foundations, was considered for downcycling purposes.

Calculations are here summarized and detailed calculations are presented in Appendix G (building characterisation), Appendix I (Emergy evaluation), Appendix J (Emergy evalution of best options for materials that will be substituted by recovered materials), and Appendix K (DE calculations).

Table 7.35. Building B2: synthesis of mass inventory.

Note Item	Mass (g)
S01: FOUNDATIONS	
S01-E01 Square base	2.63 E+07
S01-E02 Columns	9.66 E+05
Total S01	2.72 E+07
S02: STRUCTURAL FRAME	
S02-E01 Columns	1.82 E+06
S02-E02 Beams ground floor	7.33 E+06
S02-E03 Beams roof	5.48 E+06
S02-E04 Slab ground floor	1.32 E+06
S02-E05 Slab roof	5.48 E+06
Total S02	2.14 E+07
S03: FAÇADES AND ROOFS	
S03-E01 External walls	3.11 E+06
S03-E02 Doors	1.33 E+06
S03-E03 Windows	1.92 E+05
S03-E04 Roof	1.56 E+06
Total S03	5.79 E+06
S04: FLOORS	
S04-E01 External floor	1.57 E+06
S04-E02 Interior floor	3.37 E+06
Total S04	4.94 E+06
S05: INTERIOR PARTITION	
S05-E01 Interior walls	2.21 E+06
S05-E02 Doors	1.14 E+05
Total S05	2.32 E+06
S06: CEILINGS	
S06-E01 External ceilings	2.38 E+05
S06-E02 Interior ceilings	9.68 E+05
Total S06	1.21 E+06
Total mass input (g)	**6.29 E+07**

A detailed inventory is given in Appendix G.

Table 7.36. Building B2: synthesis of Emergy analysis of material flows (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Total Emergy initial input		g	6.29 E+07		2.60 E+17
Initial Emergy per gram (seJ/g)				4.13 E+09	

Detailed calculations are given in Appendix I.

Application of the equations and detailed calculations of Deconstruction Effectiveness for Building B1 are presented in Appendix K.

Table 7.37. Building B2: Deconstruction Effectiveness.

Emergy of MS (seJ)	Emergy of building B2 (seJ)	DE
1.47 E+17	2.92 E+17	0.506

7.2.3 *Building B3: wood structure system*

Building B3 is composed of a load bearing structure made of wood sections, with the following set of building materials employed as described in Table 7.38:

(i) External and internal walls: wood frame, and OSB panels;
(ii) Thermal insulation: mineral wool in external walls and floor, and structural EPS thermal insulation panel in external walls in the roof;
(iii) Roof: PVC sheet, and zinc sheet;
(iv) External walls and ceilings finishing: wood board, plywood, and varnish;
(v) External pavements: wood deck;
(vi) Internal pavements: wood floor, and varnish;
(vii) Internal walls finishing: plywood, and varnish;
(viii) Internal ceilings finishing: plasterboard, and paint;
(ix) External doors and windows: wood sections, and double flat glass;
(x) Internal doors: wood.

Figure 7.19. Building B3: 3D general view.

Figure 7.20. Building B3: 3D North view.

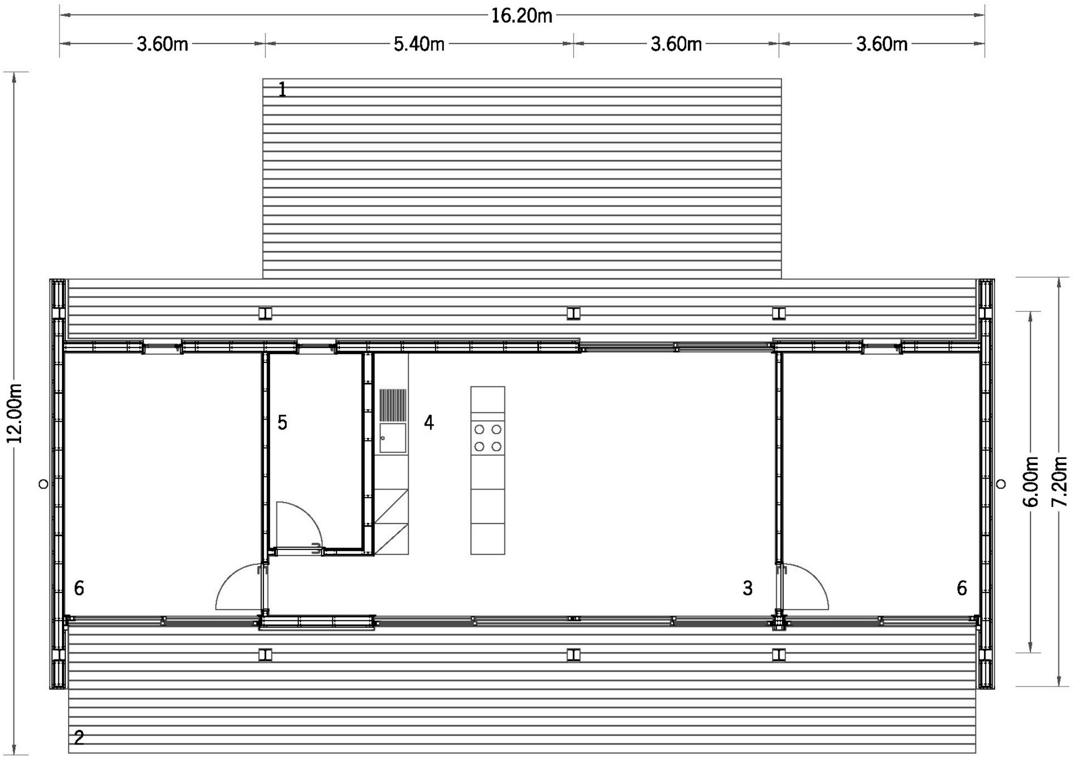

Figure 7.21. Building B3: plan
1) Terrace, 2) Balcony, 3) Living room, 4) Kitchen, 5) Bathroom, 6) Bedroom.

Figure 7.22. Building B3: 3D cross section.

The connections employed in building B3 are predominantly mechanical ones. According with the building system technology, screwing and nailing are the most employed connections.

Therefore, open connections were considered as the predominant precedence relationship for most of the materials employed in building B3 (see appendix H).

Regarding materials recovery, it is assumed in most cases that reuse recycling scenarios were feasible for the structural wood, due to their durability and the kind of connections employed. Solid wood elements, such as wall framing, wood floor, and wood board are considered as being screwed, however recycling was considered as the most feasible recovery scenario. Concerning wood panels, combustion was considered as the most feasible scenario. As considered for building B1 and building B2, other mixed waste from materials recovery, such as foundations, was considered for downcycling purposes.

Calculations are here summarized and detailed calculations are presented in Appendix H (building characterisation), Appendix I (Emergy evaluation), Appendix J (Emergy evaluation of best options for materials that will be substituted by recovered materials), and Appendix K (DE calculations).

Table 7.38. Building B3: synthesis of mass inventory.

Note	Item	Mass (g)
S01: FOUNDATIONS		
S01-E01	Square base	2.63 E+07
S01-E02	Columns	6.90 E+05
Total S01		2.70 E+07
S02: STRUCTURAL FRAME		
S02-E01	Columns	1.57 E+06
S02-E02	Beams ground floor	1.10 E+07
S02-E03	Beams roof	9.44 E+06
S02-E04	Slab ground floor	4.78 E+06
S02-E05	Slab roof	4.21 E+06
Total S02		3.10 E+07
S03: FAÇADES AND ROOFS		
S03-E01	External walls	5.54 E+06
S03-E02	Doors	1.49 E+06
S03-E03	Windows	6.74 E+04
S03-E04	Roof	6.24 E+05
Total S03		7.72 E+06
S04: FLOORS		
S04-E01	External floor	1.16 E+06
S04-E02	Interior floor	2.12 E+06
Total S04		3.28 E+06
S05: INTERIOR PARTITION		
S05-E01	Interior walls	3.00 E+06
S05-E02	Doors	6.20 E+04
Total S05		3.06 E+06
S06: CEILINGS		
S06-E01	External ceilings	3.87 E+05
S06-E02	Interior ceilings	1.00 E+06
Total S06		1.39 E+06
Total mass input (g)		**7.34 E+07**

A detailed inventory is given in Appendix H.

Table 7.39. Building B3: synthesis of Emergy analysis of material flows (without services).

Note	Item	Unit	Data (units)	Unit Solar EMERGY (seJ/unit)	Solar EMERGY (seJ)
Total Emergy initial input		g	6.29 E+07		2.60 E+17
Initial Emergy per gram (seJ/g)				4.13 E+09	

Detailed calculations are given in Appendix I.

Application of the equations and detailed calculations of Deconstruction Effectiveness for Building B1 are presented in Appendix K.

Table 7.40. Building B3: Deconstruction Effectiveness.

Recovery Effectiveness of B3 (seJ)	Emergy of B3 (seJ)	DE
1.04 E+17	2.64 E+17	0.395

7.2.4 *Synthesis of buildings evaluation*

As for the walls case studies, the model behaved as it was expected, i.e. in accordance with the properties and End-of-Life scenarios allocated to each building (see Table 7.41 and Figure 7.23 to Figure 7.26).

Table 7.41. Synthesis of the application of the proposed Model to buildings B1, B2, and B3.

	Building B1	Building B2	Building B3
Initial Mass input (g)	2.88 E+08	6.29 E+07	7.34 E+07
Renewable resources (R)	1.97 E+06	4.80 E+06	4.09 E+07
Non renewable resources (NR)	2.87 E+08	5.81 E+07	3.25 E+07
R/NR	0.01	0.08	1.26
Initial Emergy input (seJ)	9.73 E+17	2.60 E+17	1.97 E+17
Initial Emergy per gram (seJ/g)	3.37 E+09	4.13 E+09	2.68 E+09
Total Mass input (g)	2.94 E+08	6.95 E+07	9.36 E+09
Total Emergy (seJ)	1.00 E+18	5.83 E+17	2.64 E+17
Total Emergy flow (seJ/yr)	2.01 E+16	2.92 E+15	5.28 E+15
Total Emergy per gram (seJ/g)	3.42 E+09	4.20 E+09	2.82 E+09
Recovered mass (g)	2.54 E+08	5.81 E+07	7.87 E+07
Recovered mass (%)	86.5	87,6	82.7
Recovered mass for reuse (g)	1.42 E+07	1.86 E+07	2.86 E+07
Recovered mass for reuse (%)	4,7	26.5	30.1
Recovered mass for recycling (g)	2.40 E+08	3.96 E+07	5.00 E+07
Recovered mass for recycling (%)	81,7	56.6	52.6
Unrecovered mass (g)	3.98 E+07	1.18 E+07	1.64 E+07
Total Emergy flow for substituted materials	6.09 E+15	2.95 E+15	2.09 E+15
Total Emergy for substituted materials	3.05 E+17	1.47 E+17	1.04 E+17
Deconstruction Effectiveness (DE)	0.303	0.505	0.395

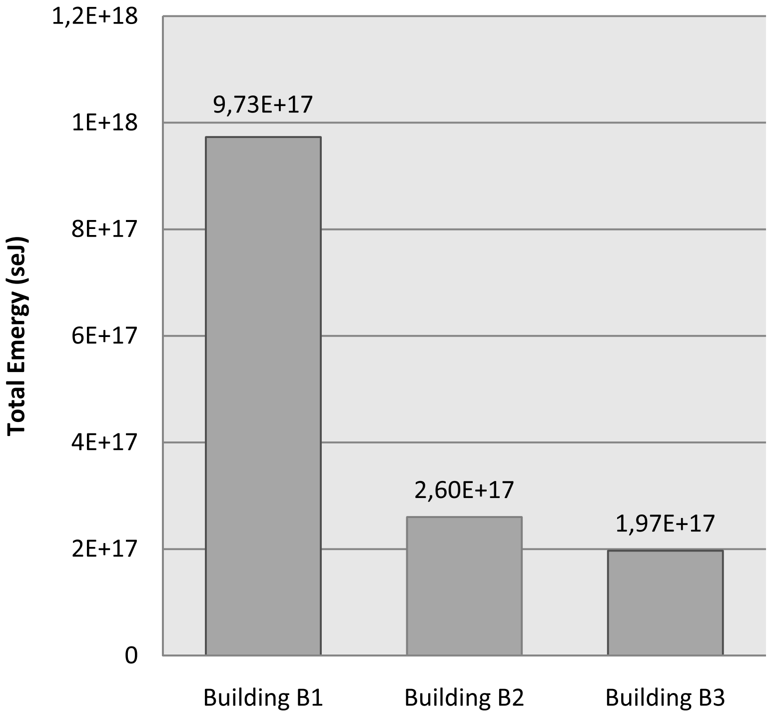

Figure 7.23. Comparison between buildings B1, B2 and B3: total Emergy input during Lifespan.

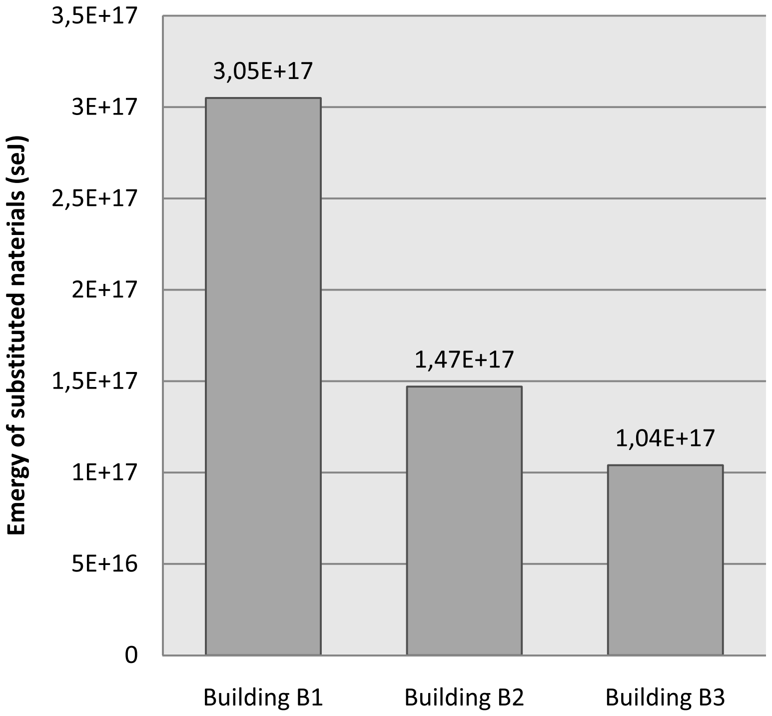

Figure 7.24. Comparison between buildings B1, B2 and B3: total Emergy of substituted materials during Lifespan.

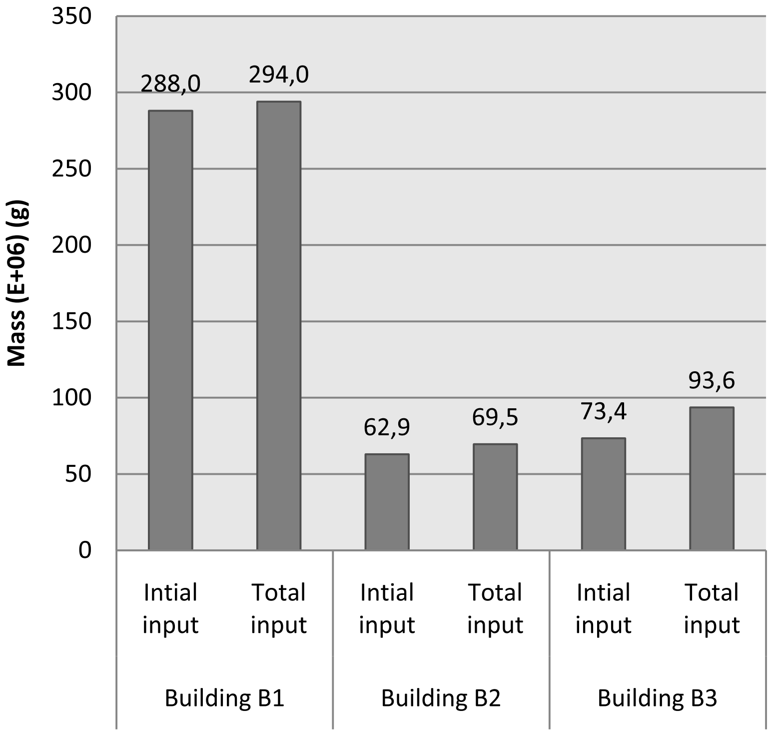

Figure 7.25. Comparison between buildings B1, B2 and B3: total mass input during Lifespan.

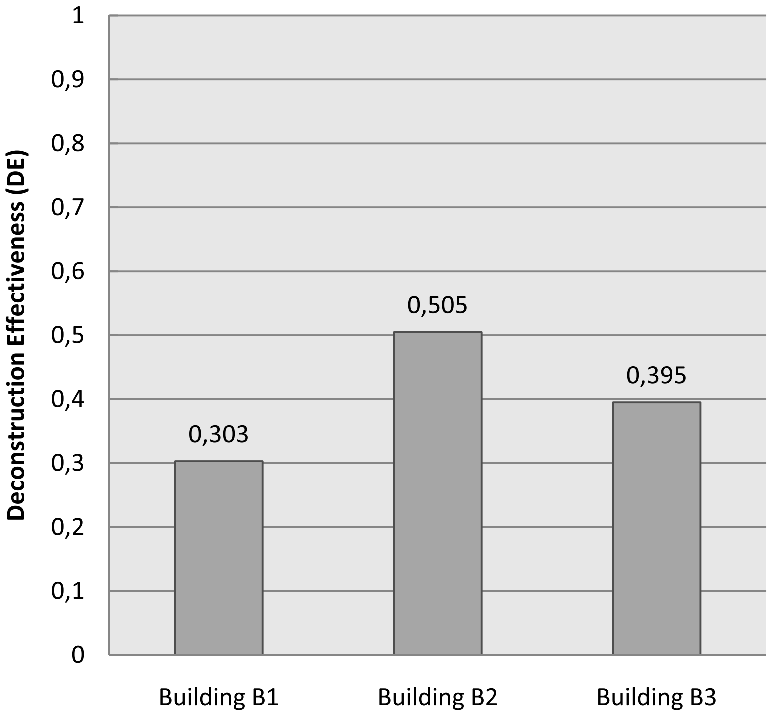

Figure 7.26. Comparison between buildings B1, B2 and B3: Deconstruction Effectiveness.

All buildings showed similar recovery rates: 86.5 for building B1, 87.6 for building B2, and 82.7 for building B3 (see Table 7.41). However differences in the Emergy of resources or materials that are saved, affect the environmental net benefit of their recovery.

Building B1 does not exhibit disassembly properties, and the reclaimed materials are in general not disassembled. In spite of the highest total Emergy input during the lifespan, mainly due to the input of materials with high density, i.e. concrete and mortars, with an Emergy per mass three times higher than the specific Emergy of the resource considered as being saved, i.e. granite. The downcycling of the recovered materials does not benefit the overall environmental performance of the building. If the concrete cast in place elements were replaced by pre-fabricated concrete columns, beams, and slabs, the DE of building B1 that would increase to around 0.675.

Both building B2 and building B3 are based on two disassemble systems and both exhibit lower mass inputs, what allows better Deconstruction Effectiveness when compared with building B1.

The core structure of building B2 is composed by steel, which has a high specific Emergy, and is reusable. Therefore, as observed in wall W2, the higher Emergy per mass of galvanized steel benefits the best options for the raw materials that are substituted. Building B2 also has the lowest Emergy and mass input throughout the building lifespan. Therefore, building B2 is the construction system with better environmental net benefit.

Building B3, in spite of being also based on a disassemble system, as observed for wall W3, does not have a high deconstruction effectiveness due to the low specific Emergy of the employed materials, i.e. wood, and the low specific Emergy of the substituted raw materials, i.e. wood logs. However, the considered end-of-life scenario of reuse of the wood structural sections benefits Deconstruction Effectiveness. If recycling of structural elements were considered instead of reuse, the Emergy flow of saved resources would decrease from 1.04 E+17 to 8.58 E+16, i.e. a reduction on 21%, and the Deconstruction Effectiveness of building B3 would decrease from 0.395 to 0.325, i.e. a reduction also of 21%.

To determine the influence of the above ground construction in the performance of building B2 and building B3, a comparison was also made without considering those elements. Such analysis allows comparing the core structure of the three houses. Without considering the foundations, all three buildings improved the Deconstruction Effectiveness.

A slight improvement of DE was obtained for Building B1 of 2% from 0.303 to 0.310. This improvement is due to overall mass reduction.

However, for building B2 and building B3 a higher DE values wer2 obtained. DE for Building b2 increased 34% from 0.505 to 0.679, and DE for building B3 improved 21% from 0.395 to 0.479. These results showed the weight of the concrete cast in place for the environmental net benefit: high mass concentration and a downcycling recovery scenario as the most feasible one, i.e. aggregates production.

7.2.5 *Alternatives to internal walls*

To assess the behaviour of the proposed Model with regard to 'Solution improvement' of the Model, the replacements of the internal wall systems was considered for building B1 (concrete structure) and building B3 (wood frame structure) by plasterboard walls.

Deconstruction Effectiveness for building B1 and building B3 had a small increase (see Table 7.42). DE for building B1 increased from 0.303 to 0.308, i.e. 2%, and DE for Building B3 increased from 0,395 to 0,421, i.e. 7%. Detailed calculations are presented in Appendix L.

Table 7.42. Synthesis of the application of the proposed Model to interior walls alternatives for buildings B1 and B3.

	Building B1	Building B2	Building B3
Initial Mass input (g)	2.85 E+08	6.29 E+07	7.26 E+07
Renewable resources (R)	1.97 E+06	4.80 E+06	4.02 E+07
Non renewable resources (NR)	2.78 E+08	5.81 E+07	3.24 E+07
R/NR	0.01	0.08	1.24
Initial Emergy input (seJ)	9.54 E+17	2.60 E+17	1.95 E+17
Initial Emergy per gram (seJ/g)	3.41 E+09	4.13 E+09	2.68 E+09
Total Mass input (g)	2.85 E+08	6.95 E+07	8.75 E+09
Total Emergy (seJ)	9.79 E+17	5.83 E+17	2.48 E+17
Total Emergy flow (seJ/yr)	1.97 E+16	2.92 E+15	4.96 E+15
Total Emergy per gram (seJ/g)	3.43 E+09	4.20 E+09	2.83 E+09
Recovered mass (g)	2.61 E+08	5.81 E+07	7.29 E+07
Recovered mass (%)	90.9	87,6	82.0
Recovered mass for reuse (g)	1.42 E+07	1.86 E+07	2.82 E+07
Recovered mass for reuse (%)	4,9	26.5	31.7
Recovered mass for recycling (g)	2.47 E+08	3.96 E+07	4.47 E+07
Recovered mass for recycling (%)	86,0	56.6	50.2
Unrecovered mass (g)	2.60 E+07	1.18 E+07	1.60 E+07
Total Emergy flow for substituted materials	6.04 E+15	2.95 E+15	2.09 E+15
Total Emergy for substituted materials	3.02 E+17	1.47 E+17	1.04 E+17
Deconstruction Effectiveness (DE)	0.308	0.505	0.421

The small increasing of DE for Building B1 is due to the Emergy per mass of steel, which mass input very low, while specific Emergy of plasterboard is similar to brick and mortar. As durability is considered the same, the parameter useful life did not have influence in DE.

The higher increase of DE for Building B3 is due to the large difference in materials quality, influenced by the higher specific Emergy and durability of the plasterboard wall when compared with the wood frame wall.

The results showed that the Model can be employed for solution improvement, being sensitive to the Emergy flow, useful life and end-of-life scenarios.

7.3 *Conclusions*

The evaluation of the proposed Model was performed both at the building element level and the whole building level. These two different scales of case studies provided information on the proposed model behaviour both regarding the reference solution and changes in the design solution with input data from architectural design.

Results obtained for the Deconstruction Effectiveness are in accordance with the qualitative expected results, both for the walls case studies and the buildings case studies.

Model is sensitive to changes in input data, regarding connection types, end-of-life scenarios, and useful life.

Deconstruction Effectiveness reinforces the importance of recovering materials with higher Emergy per mass, stressing both the role of nature work in providing those materials. This may be observed in the Emergy of the materials that are substituted by reclaimed steel and aluminium.

Durability properties are also important for the natural resources management. Results for DE also highlighted such environmental benefits, by being sensitive to mass increase over the Lifespan of the building or building element, as it was clearly observed by comparing wall W2 and wall W3.

The DE index also highlights the importance of reuse in order to maximize the environmental net benefits of materials recovery. Both wall W2 and wall W3 are examples of such environmental benefits in resource conservation. Construction systems based on high mass materials and with no disassembly properties showed to have the lowest Deconstruction Effectiveness, such wall W1 and building B1.

In accordance with the results obtained, the Deconstruction Effectiveness indicates the importance of the disassembly properties of the object under analysis, as well as its durability, the minimization of materials replacement, and the reusability of materials and components. However, Deconstruction Effectiveness showed the negative effect for end-of-life scenarios of downcycling and heat recovery, and also for materials with high cycles of replacement during the lifespan of the building or building element.

The case studies indicate the 'Effectiveness' approach showed to quantify the environmental benefits of keeping the end-of-life materials in the supply loop chain, and the efficiency in materials recovery, as showed by comparing the different DE results obtained for buildings with similar recovery rates.

One aspect to be improved is the information management within the proposed Model. Information on building characterization is very complex. However, adapting assembly/disassembly analysis tools to building construction, such as disassembly trees or AND/OR graphs, may facilitate the analysis of building Configuration and precedence relationships.

Running the model over a Building Information Modelling (BIM) platform also seems to be an important aspect for information management improvement within the proposed Model. BIM is a tool that is used to design and document a project by storing information in an integrated database. As all computed information is parametric and interconnected, data can be exchanged in a feedback loop (Kymmell, 2008). Krygiel & Nies (2008) suggest the application of BIM to manage environmental information about the building, such as water, energy, and materials by creating specific schedules and parameters.

Therefore, integrating materials properties, information parameters and calculations procedures of the proposed Model parameters within the database of the BIM model, would provide immediately information on Deconstruction Effectiveness, which could enable real time design changes.

CHAPTER 8

CONCLUSIONS

The timescale, in which industry, and construction activities in particular, consume primary resources and concentrate dispersed materials and then dispose them back into nature makes it impossible for nature to reintegrate them back in natural systems due to the limits of the carrying capacity of nature.

Construction industry has clearly a responsibility in the use of materials. Environmental performance of materials should not be focused exclusively on environmental impacts due to extraction and production. Materials selection criteria that combine environmental criteria with technological and aesthetic requirements are crucial. The way in which materials interact in order to minimize materials flow during the building lifespan and to maximize not just the amount of salvaged materials but also their quality and ability for reuse and recycling, needs to be integrated in early design phase giving rise to principles of Design for Deconstruction. This research work focused on one hand in distinguishing the governing principles of Design for Deconstruction and on the other hand developed a tool based on these principles to aid the architects in optimising the quality and quantity of the reclaimed materials for reuse or recycling. The tool may be used for existing buildings or at design stage. The following sections highlights major conclusions reached at in this research work.

8.1 *Environmental net benefits of materials recovery*

For the last three decades, industrial ecology has paid particular attention to the metabolic activities of products manufacturing, due to of the implementation of the manufacturers extended responsibility and the increasing costs of virgin, i.e. primary, materials. The emergence of ideas such as the ‘waste basket’ as a deposit of resources to be mined, and the supply loop chain, focused attentions on end of life recovery of products and materials.

However, to reach zero resources consumption the ‘waste basket’ should be entirely fed by the reclaimed materials for a closed loop chain in a zero waste scenario. One major problem with this assumption is that most recovered materials are only kept in the production cycle by means of downgrading processes, which means that new materials are continuously being fed into the system, while, at the same time part of the recovered materials is continuously discarded out of the system.

In a society with regulated consumption patterns, benefits of materials recovery may be addressed both at the economic and environmental levels. The economic benefits of materials recovery depend on the market value of the reclaimed materials compared to the costs of virgin materials. The economic value of salvaged materials is measured by analysing the costs of dismantling processes, as well as the costs of reprocessing those reclaimed materials for reuse, recycling or heat content recovery and possible disposal.

Environmental benefits, however, are more complex and thereby sometimes unclear. The environmental load of materials and products is usually measured through environmental state-pressure indicators, environmental impacts categories, or simply by comparing energy used up for processing and reprocessing, i.e. Embodied Energy.

Obviously, closing the loop of materials benefits the reduction of direct environmental impacts due to reduction in resources exploitation, manufacturing activities, and disposal of end of life goods. However, the net benefits of materials' recovery may be better understood by including the carrying capacity of our planet in the analytical framework. In fact, the Earth's role in providing natural resources by means of geological and biological processes is not often recognized and is not included in the balance.

Therefore, benefits of materials recovery should not only be assessed by the amount of recovered mass, but mainly by addressing the environmental value of reclaimed materials in comparison with the resources that are being saved by keeping those materials in the closed loop chain. In such context, benefits of materials recovery are more a question of achieving the best environmental net benefits rather than just a question of reducing non-renewable resources consumption.

8.2 *Model for estimating the Deconstruction Effectiveness index (DE)*

Several tools were developed to analyse disassemblability of buildings or to quantify the recycling potential of recovered materials due to deconstruction of buildings. However, tools to measure the environmental net benefit of materials recovery are not available.

Therefore, an attempt to develop such a tool is made in this research work proposing a model based on introducing the idea of 'effectiveness', rather than 'efficiency' in order to describe the balance between the resources that are consumed in a building, or building element, and the amount of non-extracted resources due to their recycling, or the components that are not produced due to their reuse.

The proposed model estimates the Deconstruction Effectiveness index by comparing the original environmental value of the reclaimed materials with the environmental value of materials and resources that are being saved, in order to establish a measure of the environmental net benefit of materials recovery. The proposed model addresses both quantitative and qualitative properties of recovered building materials, and highlights the role of the geobiosphere as the global recycling system, taking into account the global enhancement of carrying capacity of our planet.

Development of the proposed model is based on integration of principles of Design for Disassembly/Deconstruction (DfD) and Emergy analysis.

The first principle recognizes the role of building systems hierarchy, Service Life management, and types of connections, as the key aspects for the definition of feasible recovery patterns.

As shown by research and developments in electronics and automotive industries, disassembly plays the main role in materials recovery by providing viable means of recovering high quality materials and components.

By including DfD principles in building design, construction systems may be adapted in order to provide a flow of high quality materials for recovery, and to take into account the full advantages of materials durability, technical performance and recyclability. Including choices such as assembling processes, modular and standard components, reusable and recyclable materials and components during the design process, will highly increase the ability of materials to be easily recovered.

The second principle recognizes the role of the Earth as the main global system, where materials converge and disperse by means of energy inputs, acting according to thermodynamic principles.

Emergy analysis is shown to be a broader approach to the environmental value of materials, when compared with Embodied Energy analysis. The previous applications of Emergy analysis has shown that it is effective for estimating the net benefit ratios for building materials and recycling patterns. Previous applications of Emergy theory to building materials and recycling patterns showed to be effective for net benefit ratios. However, recycling patterns need to be better addressed in order to clarify the accounting procedures. It seems that the clearest approach is to allocate the Emergy of the resource that is being substituted to the recovered material according with recycling or reuse options.

The proposed model has a 4 steps framework that integrates: i) a database construction, ii) building configuration analysis, iii) estimating the DE index, and iv) solution improvement.

8.3 *The application and evaluation of the model*

The model can be applied to existing building analysis for evaluating the environmental benefit of the possible recovery of building elements and materials. However, its main application is in optimising decisions in DfD of new buildings. Decisions at the design stage of a building influence significantly the feasibility of dismantling operations. The disassembly properties of buildings affect both the amount and the quality of the recovered materials, and ultimately will keep the reclaimed materials in the supply chain, by means of reuse, upcycling, recycling, or downcycling processes.

For its evaluation, the model was applied to 3 different types of a building element (internal wall) and 3 different construction system of a small dwelling.

In the case of construction element the 3 different internal walls consisted of W1: brick masonry, W2: plasterboard and W3: wood frame and the evaluation intended to analyse the model's performance regarding changes to the recovery rates, lifespan, and end-of-life scenarios.

In this application Deconstruction Effectiveness index (DE) was estimated to analyse its behaviour regarding the complexity of the information generated.

For comparison, 3 different internal walls (W1: brick masonry, W2: plasterboard, and W3: wood frame), and 3 different construction systems (B1: concrete, B2: steel, and B3: wood) were compared.

For the walls case studies, DE index was equal to 0.25 for W1, 0.59 for W2 and 0.29 for W3. The better result was achieved for plasterboard wall (W2) that exhibits disassemblability properties and is composed by materials with high Emergy per mass, characteristics which are the best options for the raw materials that are saved, i.e. replaced. The masonry brick wall (W1) has a lower DE because it is based on a non-disassemblable system and downcycling recovery processes do not benefit its environmental performance. The wood frame wall (W3) has also a low DE but this is due to the low Specific Emergy of the materials employed, mainly from renewable natural resources.

Alternatives to end-of life scenarios were simulated for W2 and W3, and DE increased with better end-of life scenarios and decreased with worst end-of-life scenarios. For example, reuse of plasterboard for W2 increased the wall performance by 40%, as measured by DE, from 0.50 to 0.69. On the contrary, combustion scenarios for W3 decreased the wall performance by 30%, as measured by DE, from 0.20 to 0.14.

The results obtained indicated that the model is sensitive to changes of the recovery rates, lifespan, and end-of-life scenarios.

Furthermore, the model was applied to a whole building system (small dwelling) in order to evaluate its performance considering the complexity of the information input and output data. Three different construction systems (B1: concrete, B2: steel, and B3: wood) were evaluated using the proposed Model. The DE results were 0.30 for B1, 0.51 for B2, and 0.40 for B3. The DE index obtained showed that results are influenced by the disassemblability of the construction system, the Emergy per mass of the materials, and the end-of-life scenarios. It was also observed that the recovery rates for the three buildings are similar being 86.5 % for B1, 87.6 % for B2, and 82.7 % for B3. Hence the recovery rates did not affect the DE in the present case.

Furthermore, in order to evaluate the effect of different internal wall systems the initial internal walls of B1 and B3 were replaced by plasterboard walls. Both buildings indicated a better performance, building B1 showed an increase in DE less than 2%, however, it was more significant for B3 with a 6.5% increase of DE.

The Deconstruction Effectiveness approach seems to be a good indicator of the environmental net benefits of materials recovery, by bringing together building disassembly and environmental principles. DE index translates the quantitative and qualitative environmental properties of materials and ultimately the benefits of their recovery, both for their performance (forecast Service Life) and for their feasible recovery patterns (end-of-life scenarios), as shown by the simulations made in the case studies:

(i) Worst DE performances when end-of-life scenarios did not employ the Best Available Technology (BAT);

(ii) Similar materials recovery rates have quite different environmental benefits, due to the materials potential to be returned as raw materials by means of the best end of life scenarios.

Furthermore, the application of Deconstruction Effectiveness to a set of case studies showed that the proposed model is sensitive to the disassembly properties of the building or building element, materials durability, end-of-life scenarios and materials for which the recovered materials are a substitute.

The results provided by the case studies are in accordance with the general principles of the Emergy theory, highlighting the environmental value of the materials with higher Emergy per mass, their quality and ability to be reused or recycled.

The application of the model and the solution improvements showed that the model is a valuable tool to assist architects and engineers to improve the environmental net benefit of the building solutions, promoting buildings designed according to Design for Deconstruction principles.

Widespread use of the model requires information management and availability of further Emergy data for building materials and construction systems. When the amount of information in building configuration analysis becomes more complex the amount of information becomes difficult to manage. The introduction of tools to assist building configuration analysis, such as assembly/disassembly planning tools would be of great interest for information management.

Emergy application needs larger available data on Emergy per mass for building materials that should include also building components and products.

8.4 *Development of future work*

Dealing with information on building configuration is a key aspect of the Model. Due to the complexity of relationships established between systems, subsystems, components, and materials, a process to easily generate their precedence relations, would benefit the functionality of the model.

This aspect would benefit from the experiences in the electronics and automotive industries, where analysis of assembly/disassembly sequences have been applied to provide information on repairing and maintenance operations and on the maximization of materials recovery and minimisation of waste flow. Adaptive integration of such tools into the model would improve the data collection and management. This kind of software to analyse disassembly options would assist both Design for Disassembly/Deconstruction and the calculations of the Deconstruction Effectiveness index.

Information management could also be improved by integrating the proposed model into a Building Information Modelling (BIM) platform. This integration simplifies the usage of Deconstruction Effectiveness, and facilitates the design of buildings with regards to waste minimization and materials recovery effectiveness.