Resource metabolism of the construction sector
An application of exergy and material flow analysis

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Doctoral thesis

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NOMENCLATURE

$\Delta_f G^o$	Standard Gibbs free energy of formation (kJ/mol)
Al	Aluminum
BAT	Best Available Techniques
BOF	Basic Oxygen Furnace
C_2S	Dicalcium silicate
C_3A	Tricalcium aluminate
C_3S	Tricalcium silicate
C_4AF	Tetracalcium aluminoferrite
CDW	Construction and demolition waste
CE_xC	Cumulative Exergy Consumption
CHP	Combined Heat and Power
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
C_p	Specific heat (J/g.K)
CPR	Construction Product Regulation
Cu	Copper
DOE	Department of Energy
DMC	Domestic Material Consumption
E	Energy (J)
e_1	Energy (first law) efficiency (%)
e_2	Exergy (second law) efficiency (%)
EAF	Electric Arc Furnace
EC	European Commission
EDC	Ethylene dichloride
EEA	Extended Exergy Analysis
EKC	Environmental Kuznets Curve
ELCA	Exergetic Life Cycle Assessment
EPA	Environmental Protection Agency
EU	European Union
EX	Export

E_x	Exergy (J)
E_xA	Exergy Analysis
Fe	Iron
G	Gibbs free energy (kJ/mol)
GDP	Gross Domestic Product
GENCAT	Generalitat de Catalunya
GHG	Greenhouse Gas
GIS	Geographical Information System
GWP	Global Warming Potential
H	Enthalpy (J)
HHV	Higher Heating Value
I	Irreversibility
ICTA	Institut de Ciència i Tecnologia Ambientals
IDESCAT	Institut d'Estadística de Catalunya [Statistical Institute of Catalonia]
IE	Industrial Ecology
IEA	International Energy Agency
INE	Instituto Nacional de Estadística [National Statistics Institute, Spain]
IM	Import
IO	Input-output
ISIE	International Society for Industrial Ecology
ISO	International Organization for Standardization
kJ	Kilojoules
kWh	Kilowatt hour
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
MEFA	Material and Energy Flow Analysis
MFA	Material Flow Analysis
MJ	Megajoules
NAS	Net Addition to Stock
NO_x	Nitrogen oxides

OECD	Organization for Economic Co-operation and Development
PJ	Petajoules
PP	Polypropylene
PTB	Physical Trade Balance
PVC	Polyvinyl chloride
Q	Heat (J)
R	Universal (ideal) gas constant
ROI	Return on Investment
S	Entropy (J/K)
SETAC	Society of Environmental Toxicology and Chemistry
Sostenipra	Sostenibilitat i Prevenció Ambiental
T	Temperature (K)
toe	Tonne of oil equivalent
UAB	Universitat Autònoma de Barcelona
UN	United Nations
UNEP	United Nations Environment Programme
USGS	U.S. Geological Survey
VCM	Vinyl chloride monomer
WSSD	World Summit on Sustainable Development
Zc	

Subscripts

air	air
dest	destruction
emi	emission
gas	gas
in	input
loss	loss
max	maximum
out	output
proc	process
res	resource
tot	total
waste	waste

PREFACE

This doctoral thesis has been developed at the Department of Chemical Engineering under "Environmental Science and Technology" PhD program of the Institut de Ciència i Tecnologia Ambientals (ICTA) within the research group **Sostenipra** (Sostenibilitat i Prevenció Ambiental) of the Universitat Autònoma de Barcelona (UAB) from December 2008 to May 2013. This period includes a short research stay of three months at SupAgro, France.

Since this thesis is focused on the assessment of resource metabolism of the construction sector applying material and exergy flow analysis of the most relevant materials used in construction applications. The document is structured in five chapters.

Chapter 1 explains the theoretical framework of the thesis introducing the concepts of industrial ecology (IE), material flow analysis (MFA), life cycle assessment (LCA), exergy analysis (E_xA) including exergy efficiency and exergetic life cycle assessment (ELCA), and the general objectives of the thesis.

Chapters 2 to 4 include research contents on material and energy inputs, outputs, and net addition to stock (NAS) to the construction sector in a regional economy (Catalonia, Spain) focusing on main materials including minerals, natural rocks, ceramics, cement and cement derivatives, glass, asphalt and bituminous mix products, wood, chemicals, plastics, metals, and electric and lighting products (chapter 2); manufacturing efficiency of major non-renewable construction materials: aluminum, copper, steel, cement, concrete, ceramic tile, flat glass, polypropylene (PP), and polyvinylchloride (PVC) using exergetic efficiency analysis methodology (chapter 3); and application of ELCA in evaluating resource use efficiency of PP and PVC from life cycle point of view (chapter 3) are presented in the papers cited below. Each of these chapters has its own introduction, methodology, results and discussion, and a summary of the main conclusions for the specific field that is analyzed. In this thesis, the original contents of the following papers have been kept unchanged, which implies that minor duplications may appear in some introductory or methodological interpretations.

Chapter 2: Hoque, M. R., X. Gabarrell Durany, C. Sendra Sala, G. Villalba Méndez, L. Talens Peiró, and T. Vicent Huguet. 2012. Energy intensity of the Catalan construction sector: An application of material and exergy flow analysis. *Journal of Industrial Ecology*, 16 (5): 699-709.

Chapter 3: Hoque, M. R., G. Villalba Méndez, X. Gabarrell Durany, and C. Sendra Sala. 2013. Exergetic efficiency analysis of construction material manufacturing. To be submitted to *Journal of Cleaner Production* (June 2013).

Chapter 4: Hoque, M. R., X. Gabarrell Durany, G. Villalba Méndez, and C. Sendra Sala. 2013. Exergetic life cycle assessment: An improved option to analyze resource use efficiency of the construction sector. In: *Sustainability in Energy and Building: Smart Innovation, Systems and Technologies*, Hakansson et al. ed., 22: 313-321. Berlin, Heidelberg: Springer Berlin Heidelberg. ISBN 9783642366444.

Finally, Chapter 5 contains the general discussion, conclusions, and insights for further research. The discussion section illustrates the contributions and limitations of using exergy as a resource accounting tool and compares the results obtained in chapters 2 to 4. The conclusion section summarizes the key results introducing possible ways to overcome the limitation for improved resource metabolism of the construction sector.

Annex A summarizes the results of a case study that has been performed during the short research stay at SupAgro, France within the “Ecotech Sudoe” project. It highlights the energy savings potential that can be obtained through implementing intelligent techniques (intelligent low energy lighting and architectural sun screening solution), material selections (aluminium double glazing window frames and joinery, inside cork insulation), and improved solutions for heating and ventilation systems related to the renovation of a building at SupAgro for tertiary activities (classrooms and offices). Real time energy consumption after renovation of the building has been monitored and compared with the building energy demand in Mediterranean region, using a simulation tool.

All references in this thesis follow the style as recommended by the *International Journal of Industrial Ecology*.

SUMMARY

This thesis aims to assess the resource consumption of the construction sector, and the wastes and emissions generated by the sector. This is motivated by the fact that the construction sector is responsible for large amounts of resource consumption and represents nearly 9% gross value added to the world's gross domestic product. The assessment considers the life cycle perspective from raw material extraction, through construction product manufacturing, material transport, construction and demolition waste generation, to waste transport, treatment, and final disposal. The aim is to pinpoint the opportunities for improved material selection criteria, processing, reuse, and recycling for sustainable resource use. Due to the system complexity of buildings and infrastructure, composed of many interacting components, it is always challenging to undertake an accurate resource accounting within this sector. In this perspective, the concepts of material flow analysis (MFA), life cycle assessment (LCA), and exergy analysis (E_xA) are discussed as resource accounting tools focusing on their applications in the construction sector. Apart from sectoral analysis, this thesis also analyzes the efficiency of manufacturing processes and products' complete life cycle based on exergy. All the processes and products selected are relevant for the construction sector, and this analysis aims to provide deper insights into sectoral material use.

Chapter 1 details the theoretical framework under which exergy and material flow analyses are used in assessing the resource metabolism of the construction sector highlighting the importance of this sector in terms of resource flows, and generation of waste and emissions. This chapter also introduces the exergy efficiency and exergetic life cycle assessment (ELCA) tools, explaining the limitations of energy analysis and LCA, and how the application of these exergy-based methods can provide better insights into resource use efficiency in manufacturing processes and throughout the products' life, respectively. Industrial ecology (IE) is presented to introduce the systems-based approach and thermodynamic framework on which of the construction sector is analyzed in this study.

Chapter 2 presents the results of material and exergy flow analyses of the Catalan construction sector for the year 2001. In 2001, Catalonia had an additional 52 million tonnes of material stock to the sector and generated 7 million tonnes of construction and demolition waste (CDW) of which only 6.5% were recycled or reclaimed. The study

shows that manufacturing stage consumes the largest fraction of energy resources during the products' whole lifecycle followed by material transport, accounting for 57% and 4% of exergy use, respectively. It is pointed out that improvement in material selection, manufacturing technologies, and design for disassembly lead to sustainability of the sector delivering improved resource use efficiency.

In chapter 3, the exergetic efficiency of the production processes, both primary and secondary (recycling) production process, of construction materials is calculated in order to assess material quality, exergy losses, and process improvement potentials. This serves to quantify the improvement potentials for present manufacturing processes addressing the manufacturing inefficiencies of nine major non-renewable construction materials: aluminum, steel, copper, cement, concrete, ceramic, glass, polypropylene (PP), and polyvinyl chloride (PVC). Exergy efficiency based on the second law of thermodynamics is determined in order to compare the theoretical exergy efficiency and the real-process exergy efficiency. The large difference between theoretical and empirical exergy requirements in manufacturing processes suggests that opportunities for better industrial exergy utilization still exist but require design and/or technology improvements. The results demonstrate that resources are utilized more efficiently in recycling processes compared to primary manufacturing processes.

This thesis has presented an effort (chapter 4) to pinpoint how efficiently resources are used in the construction applications, using exergetic life cycle assessment methodology in a cradle-to-grave life cycle approach. This included raw material extraction, resin manufacturing, and end-of-life waste management life-cycle stages. The irreversibility during the complete life cycle allows to evaluate the degree of thermodynamic perfection of the production processes and to conduct the assessment of the whole process chain. Overall life cycle exergy efficiency of PP and PVC is quantified 27.1% and 9.3%, respectively, characterized by a low efficiency of manufacturing and recycling processes for both materials. From resource conservation point of view, mechanical recycling has been suggested as the viable option for end-of-life plastic waste management, since it loops materials back directly into new life cycle and reduces primary resource inputs in the production.

CHAPTER 1

Introduction and objective

Source: www.internationaltradenews.com

1.1 Introduction

World population is expected to increase by 2.3 billion between 2011 and 2050, from 7.0 billion to 9.3 billion. At the same time, the population living in urban areas is projected to increase by 2.6 billion, from 3.6 billion in 2011 to 6.3 billion 2050 (UN 2011). Thus, the urban areas of the world are expected to absorb the major population growth over the next four decades. As a result of this projected massive urbanization, it is widely recognized that conservation of natural resources is vital for sustainable development. However, the flows of natural resources to the construction sector are not yet satisfactorily evaluated. This thesis focuses on the assessment of mass and exergy flows within the construction sector, including both in buildings and infrastructure. The outcomes of this evaluation can be used to optimize resource metabolism, with the aim of increasing resource use efficiency in construction applications.

Buildings and infrastructure are considered as complex system, composed of many interacting components. For instance, network of infrastructure include transportation networks, waterway networks, pipelines for gas and petroleum, electrical grids, dams, telecommunication networks etc. Due to complex interactions and interdependencies between individual systems, urban environments can be viewed as a “system of systems”.

Since resources are limited, their management must be carefully planned. However, it is simply impossible to manage the resources effectively if we do not know what quantity is available, at which rate these are depleting, and how efficiently the resources are utilized within the construction sector. In this context, it is important to make a sound resource accounting of this sector in order to assess its sustainability that requires comprehensive information of all relevant flows and stocks of materials, from production to use and final disposal at the end of the lifespan. This information enables to understand how capital resources (stocks) of the construction sector change over time such as in quantity, quality, composition, and service delivered. These changes can be the results of changing socio-economic and demographic patterns in society, changing regulation and technology, and the inevitable fact that stocks are ageing with time and thus exposed to new challenges in operation, maintenance, refurbishment, and management. Building and infrastructure system also uses diversified material and energy resources. As a result, it is always challenging to undertake an accurate resource accounting within the construction sector. In order to overcome the limitations, this dissertation discusses the role of resource accounting from several key perspectives such as resource inputs in construction applications, conservation of energy and material, process improvement potentials, and waste and emissions associated with construction materials.

This introduction section aims to provide an overview of the global construction sector and to establish the framework under which exergy and material flow analyses are used in assessing the resource metabolism of this sector. This section presents industrial ecology framework as a discipline (sub-section 1.1.1) for sustainability assessment of the construction sector. It then highlights the importance of the construction sector in an economy in terms of resource flows, and waste and emissions generated by the sector (sub-section 1.1.2). The preceding two sections of this chapter describe the application of material flow analysis (MFA) and exergy analysis (E_xA) tools for the evaluation of resource flows in the construction sector (sub-sections 1.1.3 and 1.1.4, respectively), which are applied in **Chapter 2** of this thesis to assess the exergy flows of the Catalan construction sector. Sub-section 1.1.5 details the exergy efficiency and exergetic life cycle assessment (ELCA) tools. This sub-section explains how the application of these exergy based methods can provide better insights into resource use efficiency, eliminating the limitations of energy analysis and life cycle assessment (LCA). Exergy efficiency and ELCA tools are applied in **Chapter 3 and 4** in order to assess improvement potentials of manufacturing processes and throughout the products' life cycle, respectively. Section 1.1 finishes discussing the necessity of thermodynamic analysis to obtain improved sustainability of the construction sector (sub-section 1.1.6). Finally, the objectives of this thesis are enumerated in section 1.2.

1.1.1 Industrial ecology framework

The industrial ecology (IE) concept integrates industrial ecosystems with natural ones, was already used in the 19th century (Fischer-Kowalski 1998, Fischer-Kowalski and Hüttler 1999). The metabolism of the industrial system can be described through "material balance" for a production unit or for a geographical region. IE, however, goes beyond assessing the material and energy flows and allows to understand how the industrial system works, how it is regulated, and its interaction with the biosphere (Erkman 1997). It provides more sustainable solutions in the development growth path through employing life cycle thinking and minimizing waste generation (Ayres and Ayres 2002). IE is defined as "a systematic and integrated way by which an industrial system is viewed not in isolation from its surroundings but in concert with them. It is a systems view in which one seeks to optimize the total material cycle from virgin material, to finished material, to component, to waste product, and to ultimate disposal" (Jelinski et al. 1992; Graedel and Allenby 1995).

With the emergence of IE, efforts to reduce the resource depletion and to move toward more sustainable patterns of resource use have intensified in recent years (Graedel and Allenby 2003; Graedel 1996). One of the main focuses of IE is to advance design-oriented and inter-industry strategies for resource conservation. It gives emphasis to the avoidance of waste generation and/or reuse of waste products with the goal of developing more mature industrial ecosystems that exhibit increasingly cyclical resource use patterns, from linear (open loop) to closed loop systems, analogous to those observed in biological ecosystems (Ayres 1989). Allenby (1992) has described this change as the evolution from a type I to type III system, as shown in figure 1.1. Type I system is depicted as a linear process in which materials and energy enter one part of the system and then leave either as products or by-products/wastes. Because wastes and by-products are not recycled or reused, this system relies on a large, constant supply of raw materials. Unless the supply of materials and energy is infinite, this system is unsustainable; further, the ability for natural systems to assimilate wastes (known as "sinks") is also finite. In type II system, which characterizes much of our present-day industrial system, some wastes are recycled or reused within the system while others still leave it. Type III system represents the dynamic equilibrium of ecological systems, where energy and wastes are constantly recycled and reused by other organisms and processes within the system. This is a highly integrated, closed system. In a totally closed industrial system, only solar energy would come from outside, while all byproducts would be constantly reused and recycled within the system. Type III system represents a sustainable state and is an ideal goal of industrial ecology.

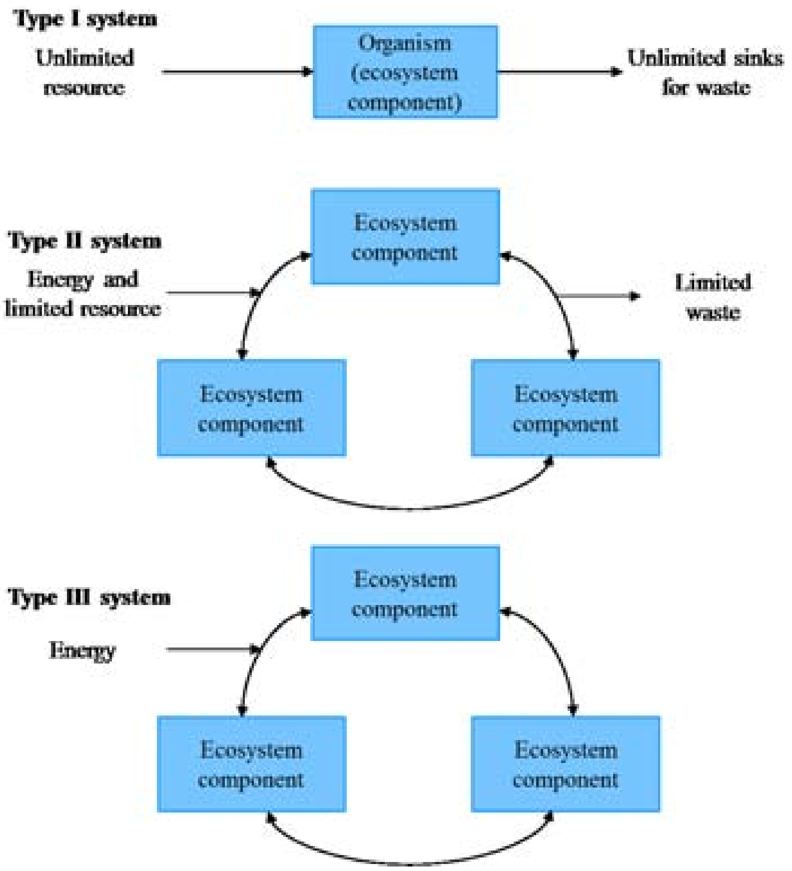

Figure 1.1: System types, evolution from open loop to closed loop system [Adopted from Allenby (1992)].

In the IE literature, an expanded role for waste avoidance and reuse is explored not only on the level of finding new sinks for existing waste streams, but also by attempting to incorporate re-usability into product and process design (Graedel 1996). Perhaps the best known of the IE approach uses some lessons learned from the observation of ecosystem behavior to make better use of resources by using existing industrial waste streams as resource inputs to other industrial processes.

Like natural systems, construction sector consumes material, energy, and water flows, transforming them into products and wastes. From IE point of view construction sector should provide an efficient method for accumulated resources to be used in the future instead of being waste. Design for disassembly at both buildings/infrastructure and construction products levels are therefore vital for resource conservation. The success of reuse and/or recycling relies not only on effective recovery strategies, but also on the availability of materials from buildings and infrastructure that are easily recyclable. In general, materials that can be processed in relatively pure form offer a higher recycling return than composites (Rathmann 1998). Thus, appropriate material selection for buildings and infrastructure, which are easily recyclable and has higher life cycle energy benefits, is one of the top most aspects that needs to be addressed while designing stage.

1.1.2 Economic growth, resource flows, and environmental damage

According to the hypothesis of dematerialization, there is a reduction in material and energy consumption along the economic growth path, therefore the use of less energy and material resources to produce the same economic output could represent a solution to the ecological compatibility of future economic growth (Ramos-Martin 2005). From an environmental standpoint, the hypothesis of the Environmental Kuznets Curve (EKC)[1] states the existence of an inverted-U shaped relationship (figure 1.1), indicating a 'delinking' of environmental pressure from economic growth in relation to rising per capita incomes: environmental degradation increases with economic activity up to a turning point after which increase in income contribute higher environmental quality (Grossman and Krueger 1991; Shafik and Bandopadhyay 1992).

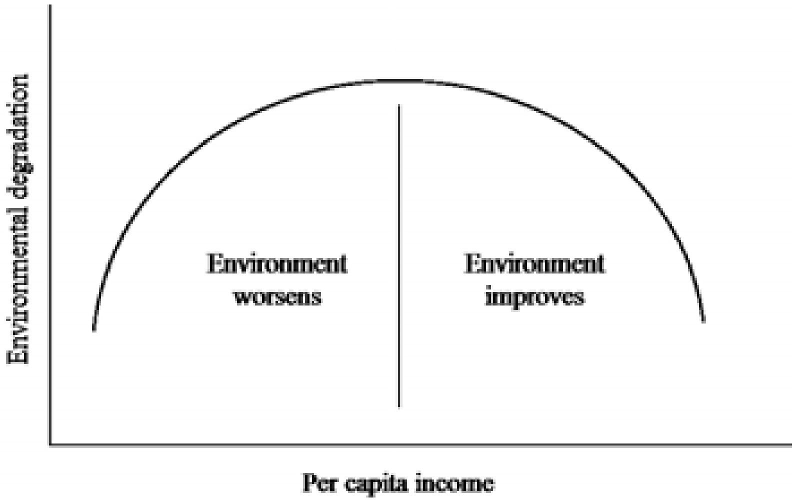

Figure 1.1: Environmental Kuznets curve.

The metabolic exchange of energy and material resources between nature and technosphere constitutes the key to most environmental problems since any resource taken from the environment ends up in the environment sooner or later as emission or waste, representing a linear model system. Thus, any strategy of reducing the inputs also reduces the overall outputs, and may thus contribute to the mitigation of environmental

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[1] This theory was named after Kuznets (1955), who hypothesized income inequality first rises and then falls as economic development proceeds.

impacts. Delinking may not be persistent and increase in material consumption may show an N-shaped curve rather than an inverted U. As for example, in late 1980s Belgium, Luxembourg, Italy, Japan, Spain, Germany and the United Kingdom show an upswing in their throughput intensities. Thus, their throughput rose more than their increase in GDP, which is indicative of a period of relinking (De Bruyn and Opschoor 1997). Dematerialization in absolute terms for a resource intensive sector like construction may not be possible since this sector requires an important material basis for operation. It has been stated that the scarcity problems that the society could be facing are based on the use of materials, rather than on the use of energy sources. This is why material recycling, a promising means of dematerialization, has become essential in order to be consistent with the sustainability doctrine.

Construction materials are important in an economy because of the immense social and environmental impact associated with extraction, processing and maintenance activities. Construction is considered as a “service” sector with an important connection with manufacturing and other industries such as transport, mining, energy etc. Thus, this sector has a major influence on the economy, the natural environment, and the society. Currently the sector is using a large number of the earth’s resources and producing environmental burdens in different stages of construction activities. Since construction sector is one of the major generators of solid waste, the question arises what percentage of construction and demolition waste is reusable or recyclable? What happens to the waste from construction of buildings/infrastructure or demolition/ maintenance activities? What is the potential for recycling materials resulting from construction and demolition operations? The satisfactory answers of these questions can only be obtained from a detailed biophysical evaluation of the construction sector that explains the types and quantity of material use, the complexity of manufacturing and recycling processes of these materials as well as information concerning construction and demolition processes.

The focus of this dissertation is not to assess the dematerialization of the construction sector or the implication of dematerialization but to demonstrate the potentials of material selection and recycling of CDW for improved sustainability of this sector that may lead to an overall dematerialization delivering reduced environmental impacts. In order to address this objective, a detailed evaluation need to be performed concerning resource flows into the construction sector including both material and energy, generation of CDW and emissions, reuse and recycling of materials, process efficiency (both manufacturing and recycling), and potentials of using recyclable materials. This work is equally concerned with the amount and the composition of materials including waste and emissions generated by the sector.

1.1.3 Material flow analysis (MFA)

MFA is a systematic tool for the assessment of flows and stocks of materials within a system defined in space and time (Brunner and Rechberger 2004). A mass balance framework can promote a better understanding of the flow of resources, and the impact of human activity on surrounding ecosystems, strengthening informed decision making.

The most wide-spread methodology for the assessment of material flows in a regional or country-level is economy-wide MFA as explained by Eurostat (2001), which stands as a basis for the compilation of a set of material flow indicators. For a consistent compilation of economy-wide material flow accounts, it is first necessary to define the boundary between the economic and the environmental system, representing which elements of the material world belong to the system and which to it environment, since only resources crossing this border are accounted (Hammer et al. 2003).

MFA provides a comprehensive picture of the environmental pressures, and inter-link the production and consumption of a country or region by illustrating the relations between resource extraction, production, consumption, and final disposal. Since environmental pressures and impacts associated with material flows are mostly site-specific, it is reasonable to disaggregate the material flow indicators accordingly such as for smaller regional units including cities, districts, provinces (Kovanda et al. 2009).

Most commonly used MFA indicators include domestic extraction (DE), physical imports (IM), physical exports (EX), physical trade balance (PTB), direct material input (DMI), and domestic material consumption (DMC).

The DE indicator is calculated as the sum of the physical quantity of raw materials extracted (energy raw materials, ores, industrial and construction minerals) and biomass harvested (crop and timber harvest, hunting, collecting of berries, mushrooms, etc.) in the territory of a particular country, region or city (Eurostat 2001). DE can be directly related to regional population, area, and GDP to allow for inter-regional comparisons.

The IM indicator is defined as the physical quantity of all imports, including imports of raw materials, biomass, semi-manufactured products and final consumption products. The EX indicator is defined analogously to IM, i.e. quantifying physical exports. In the case of countries, imports and exports refer to international trade while in the case of cities and regions; they refer to material flows crossing the boundaries of such administrative units. Therefore, they cover imports and exports both from and to other countries and from and to other cities/regions of the same country. PTB can be obtained by subtracting EX from IM, which expresses the balance of these shifts: if positive, the given spatial unit exerts pressure on other regions through its trade; if negative, the situation is inverted. Since IM contains flows coming from many countries or regions, it is difficult to relate them to such reference scales as area or population.

The DMI indicator is calculated as DE plus IM and measures the direct input of materials for use into the economy, i.e. all materials that are of economic value and are used in production and consumption activities. The DMC indicator is calculated as DMI minus EX and gives information on the quantities of resources consumed by a given spatial unit.

The main goal of applying MFA in the construction sector is to quantify the inputs to the stock of buildings and infrastructure, and to quantify the outputs released to the environment or being exported. The input materials entering to the stock are raw materials extracted from the environment; processed or manufactured materials produced; and secondary materials such as materials originated from recycling activities within the boundary or abroad. On the output side, flows to the environment can be released either as waste or by dissipative losses from buildings and/or infrastructure.

A number of studies have attempted to estimate the material inputs (either selected materials or aggregated) to the construction sector (Federici et al. 2008; Hashimoto et al. 2007; Hoque et al. 2012; Smith et al. 2003; Woodward and Duffy 2011), waste generation from construction and demolition (C&D) activities (Coelho and de Brito 2011; Garrido et al. 2005; Kofoworola and Gheewala 2009; Bergsdal et al. 2008), assessing environmental impacts (Coelho and de Brito 2012; Klang et al. 2003; Ortiz et al. 2010), management of generated waste (Thosmas et al. 2009; Coelho and de Brito 2007; Peng et al. 1997; Fatta et al. 2003; Río Merino et al. 2010;), and the economic feasibility of managing CDW (Coelho and de Brito 2013; Duran et al. 2006; Nunes et al. 2007; Zhao et al 2012).

A common problem encountered in estimating CDW generation is the lack of sufficient statistics and data on C&D activities. In general, statistics are more comprehensive for construction activities than for demolition activities (Kohler and Hassler 2002; Bergsdal et al. 2007). Besides, statistics based on material use in old buildings/ infrastructures are not readily available. It is widely recognized that the recycling of CDW in the future can be confronted with the problems of increasing complexity of materials requiring a higher degree of knowledge about the individual components of combined construction materials and selective methods for the demolition of construction. Recent initiatives on the implementation of building code, such as Eurocode, and construction material regulations, such as EU construction product regulation (CPR 2011), may lead to an improved sustainability of the future construction sector.

Statistics on building stocks are more comprehensive than for infrastructure. Due to this limited data availability, total stock of construction is difficult to estimate in any economy. Table 1.1 shows total dwelling stocks in European countries, demonstrating the dwelling intensity[2] in respective countries. It is observed from the table that some of the EU-12[3] member states, such as Slovakia, Poland, and Romania, still have much lower dwelling intensity compared to EU-15 countries. Thus, it is expected that new construction will be dominated in EU-12 member states in the coming years, which is also presented in recent studies on European housing sector (Pittini and Laino 2011; Dol and Haffner 2010; IHS 2010). In order to account for the stock of construction materials, a stepwise approach can be performed that requires time series material inputs and outputs of the construction sector. To limit the scope of the study, this thesis aims to quantify net addition to stock (NAS) of the Catalan construction sector.

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[2] Dwelling intensity can be defined as the number of dwelling per 1000 inhabitants.

[3] EU-12 countries are the 12 member states of the European Union (EU) after the enlargement on 1 May 2004 and include: include Bulgaria, Czech Republic, Estonia, Cyprus, Latvia, Lithuania, Hungary, Malta, Poland, Romania, Slovenia, and Slovakia.

Table 1.1: Dwelling intensity in the EU in 2009

Country	*Dwelling intensity*	*Total dwelling stock*
Spain	544	25129000
Finland	531	2784000
France	509	31264000
Denmark	500	2680000
Germany	490	39268000
Estonia	485	651000
Sweden	479	4508000
Belgium	457	5043000
United Kingdom	443	27108000
Netherlands	431	7107000
Hungary	429	4303000
Romania	390	8329000
Poland	348	13302000
Slovakia	326	1767000

Data source: Dol and Haffner 2010

This thesis mainly focuses on assessing resource flows (both material and energy) of the construction sector at regional-level. Compared to the large number of MFA studies on the national level, published studies on the regional or local level are still very limited and a standardized method such as presented by Eurostat (2001) for the national level does not exist yet. The estimation of interregional trade is one of the most important issues and at the same time one of the less frequently analyzed features within a regional economic system of accounts (Rueda-Cantuche 2005). This is of particular relevance at the current time because increasing political emphasis is placed on sustainable resource management and resource productivity at the EU level. However, the implicit cost of collecting required information as well as unavailability of interregional trade flow data making it difficult to account for the flows of construction materials in a regional economy.

A main difference between national and regional MFAs concerns the data sources. National level data are more readily available from statistical offices directly in published form in physical units whereas data availability is much smaller on a regional level, making it time consuming process since regional data are mostly dispersed among several institutions. Besides, data may not be available in physical units for all the flows and therefore may have to be estimated from more general data such as from monetary unit. Two main methodological differences between the national and the regional level concern export and import flows and confidentiality of data. National levels trade flows are reported by official statistics for the whole country. Regional trade flows on the other hand might be separated into intraregional, interregional, and international trade flows (both flows between the region and the rest of the country, and region and the rest of the world outside the country). In quantifying the various components of the mass balance, interactions among the sub-systems need to be considered to avoid double counting, since sector-specific flows are interconnected such as minerals are used as raw materials to produce cement. This approach allows the use of material resources to be directly identified with their end use.

MFA provides important information on the amount of materials involved, and waste and emissions generated from a system. However, this tool alone is not sufficient to address in what compartment the potential losses of material and energy resources take place and where greater improvement potentials exist. Exergy analysis on the other hand illustrates the thermodynamic inefficiency of a process or a system, including all quality losses of energy and materials (Branham et al. 2008). Therefore, a better representation of resource use can be assessed by using exergy-based analysis. This thesis uses E_xA methodology together with MFA in order to provide useful insights into resource metabolism of the construction sector.

1.1.4 Exergy analysis and irreversibility

In general, energy resources are assessed in terms of energy content, allowing a direct comparison between them, and non-energy minerals are assessed in terms of tonnage and grade. If resources are measured through the second law of thermodynamics in terms of exergy, all the characteristics of energy and material resources such as quantity, chemical composition, and concentration can be integrated in a single indicator (Valero et al. 2010). Thus, it can be used as a global indicator, allowing the comparison among different energy and material resources. Unlike standard economic valuations, the exergy analysis gives objective information since it is not subject to monetary policy, or currency speculation (Valero Delgado 2008). (Cornelissen 1997; Bejan et al. 1998).

Exergy designates the quality or availability of energy. Energy can be transformed but is always conserved as states the first law of thermodynamics. Exergy in contrast, is consumed in all real world processes as entropy is produced, according to the second law of thermodynamics (Szargut 2005). It can be defined as the maximum amount of work that can be obtained from a system at thermodynamic equilibrium with its surroundings by a sequence of reversible processes (Szargut et al 1988). Since exergy is a property of both the system and the environment, it is always evaluated with respect to a reference environment, also termed as dead state due to the fact that the exergy is zero. Thus, the reference environment needs to be specified in order to calculate the exergy. The environment performs the function of the reservoirs of thermal, mechanical and chemical energy, and its intensive properties such as temperature, pressure, and chemical potential do not change significantly as a result of slight changes in environmental conditions. This study performed exergy calculations defining the environmental conditions as 1 atmosphere and 25°C, as stated in Szargut and colleagues (1998), unless otherwise specified.

The chemical exergy of a compound depends on its composition. If the composition is known, the chemical exergy can be calculated on the basis of the chemical formation reaction, utilizing the Gibb's free energy of formation and the exergy of the chemical elements in the substance (equation 1.1). If the material is considered to be a mixture, then the chemical exergy of the mixture is calculated by summing the exergy of the mole fractions, as illustrated by equation 1.2 (Finnveden and Ostlund 1997; Szargut et al. 1998). The chemical exergy of a mixture containing *n* pure chemical species at the environmental state (T_0, P_0) is calculated by equation 1.3.

$$e^{0}_{ch,i} = \Delta_f G^{o}_{i} + \sum_{el} n_{el}\, e^{0}_{ch,el} \qquad (1.1)$$

$$E_{ch} = \sum_{i} n_i\, e^{0}_{ch,i} \qquad (1.2)$$

$$e_{ch} = \sum_{i} n_i\, e^{0}_{ch,i} + RT_0 \sum_{i} n_i \sum_{i} X_i \ln X_i \qquad (1.3)$$

where, $\Delta^f G^o_i$ is the standard Gibbs free energy of formation of the substance *i*; n_i is the number of moles of substance *i*; e^0_{ch} is the standard partial molar exergy; $e^0_{ch,i}$ is the partial molar chemical exergy of substance *i*; e_l is the elements in substance *i*; and E_{ch} is the chemical exergy of the substance; R the ideal gas constant (8.3149 J/mol.K), T_o the absolute reference temperature (298.15 K), and X_i the molar fraction of species i in the material. The first term in equation 1.3 is the contribution to the exergy content made by each fraction of the pure compounds, while the second term accounts for exergy variations caused by mixing of different species, assuming an ideal solution.

E_xA makes it possible to universally compare different processes and alternative process routes on a thermodynamic basis. This concept can demonstrate how much exergy is supplied to a system and how much of this is discarded into environment through entropy generation also termed as 'exergy consumption'. Thus, it can be used as an efficient tool to account for the use of energy and material resources providing information on how effectively a process takes place towards conserving natural resources.

Since pollution is proportional to the extent of energy utilizations of processes, exergy is considered to be linked to environmental impact (Ayres 2001). The irreversibility of the real processes implies exergy destruction and waste flow to the environment. The exergy embodied in the wasted residual could be a measure of the potential for causing damage in the environment.

Exergy is lost in all processes, mostly, but not entirely, as low temperature heat or in the form of chemically or physically reactive materials. To estimate the exergy of waste, detailed chemical composition of waste stream is required. Once this is known, an exergy balance of a process can be obtained, as illustrated in equation 1.4:

$$E_{x,\mathrm{in}} = E_{x,\mathrm{prod}} + \Delta E_{x,\mathrm{proc}} + E_{x,\mathrm{waste}} \qquad (1.4)$$

where, $\Delta E_{x,\mathrm{proc}}$ is the exergy destruction in the process due to the necessary forces that drive the process; $E_{x,\mathrm{in}}$, and $E_{x,\mathrm{prod}}$ represent the exergy of inputs and useful outputs, respectively; $E_{x,\mathrm{waste}}$ is the exergy of waste including emissions.

A practical difficulty in accounting process exergy loss (exergy destruction plus exergy of waste) is that for many processes it is difficult to obtain reliable data on the chemical composition of waste. However, the composition of process waste streams can be estimated knowing the inputs and basic chemical reactions, as well as temperatures, pressures and yields (Ayres et al.1998).

It is estimated that construction materials account for more than half of domestic extraction (Hass and Popescu 2011). Thus, the destruction of the exergy reservoirs of natural resources has to be minimized, in order achieve a sustainable construction section, to a level at which there be negligible damage to the environment and exergy supply will be secured for future construction applications. Exergy function can be used as a potential tool for resource and/or emissions accounting (Szargut et al. 1988; Dincer and Rosen 1999). Exergy analysis shows where the work potential of natural resources in relation to the surrounding environment is lost, i.e. where the irreversibility or exergy destruction takes places (Szargut 1978). The maximal obtainable potential of work of a flow can only be obtained via reversible processes as shown by process I in equation 1.5. The equation illustrates that there is no emission to the environment and no depletion of resources in a reversible process.

Process I: $E_{x,res} = E_{x,prod;}$ no depletion and no emission (1.5)

In general, real world processes are irreversible as shown in process II in equation 1.6.

Process II: $E_{x,res} > E_{x,prod} + E_{x,emi;}$ depletion and emission (1.6)

The process demonstrates irreversibility and emission in terms of exergy. Exergy can also be used as a more general criterion, where emissions can be prevented or separated and transformed to harmless waste or useful products. When all exergetic emissions are handled by these processes the environmental burden of products can be compared by only the criterion of irreversibility as shown in process III in equation 1.7.

Process III: $E_{x,res} > E_{x,prod;}$ depletion and no emission (1.7)

where, $E_{x,res}$, $E_{x,prod}$, and $E_{x,emi}$ represent exergy of resource, product, and emission (including waste), respectively.

In this thesis, exergy and material flow analyses are used to quantify the inputs and outputs of the Catalan construction sector. Based on the mass balance principle, exergy balance of the sector is estimated. The assessment aims to attract attention to policy makers, practitioners, and end users regarding material selection and potential benefits of CDW recycling. The case study presented in chapter 2 demonstrates how much exergy can be recovered from CDW. Since construction sector plays an important role in

Catalan economy, representing nearly 8% gross value added (GVA)[4] to the gross domestic product (GDP), utilizing the outsomce of the case study will optimize the sustainability performance of this resource intensive sector.

1.1.5 *Exergy efficiency and exergetic life cycle analysis*

In an energy analysis, based on the first law of thermodynamics, all forms of energy are considered to be equivalent. The quality degradation of energy is not taken into account. For example, the quality change of thermal energy while transferred from a higher to a lower temperature can not be demonstrated in an energy analysis since it shows the energy flow to be continuous (Cornelissen 1997). Exergy analysis on the other hand, shows the thermodynamic imperfection of a process, including quality degradation of materials and energy. Exergy efficiency is considered to be a useful tool in order to assess the energy conversion, irreversibility, and process improvement. An important strategy for improving the sustainability of systems is to reduce the rate of exergy loss (also termed as exergy consumption) or entropy production, in other words to increase the exergy efficiency. Different ways of formulating exergetic efficiency are explained in details by Cornelissen (1997). This thesis uses the exergy efficiency (e_2) as the ratio of the useful exergy output ($E_{x,\mathrm{out}}$) and the exergy needed ($E_{x,\mathrm{in}}$) to obtain that output including materials and utilities, as expressed in equation 1.8:

$$e_2 = \frac{E_{x,out}}{E_{x,in}} \tag{1.8}$$

The numerator represents the material exergy of the useful output product produced by the process. The word ‘useful’ is potentially ambiguous since in economic terms useful products are those outputs with a well-defined market and market price (Ayres 2005). In practice, some of the process outputs can be used as inputs for the same facility or other downstream products or processes, without having market prices. For instance, low quality exhaust heat from glass melting furnace can be usable in preheating raw materials, but not marketable outside the facility.

Various extensions of exergy analysis such as Cumulative Exergy Consumption ($\mathrm{CE_xC}$) analysis (Szargut and Morris 1986), ELCA (Cornelissen and Hirs 2002), and Extended

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[4] GVA data adopted from Institut d'Estadística de Catalunya (IDESCAT). Despite the recent recent economic crisis, Catalan construction sector shows a growth of 34% GVA between 2001 to 2007.

Exergy Analysis (EEA) (Sciubba 2001) have been developed in the past to analyze industrial systems. CE_xC accounts for all the inputs from natural resources to obtain a final product. ELCA uses cumulative exergy contents of the inputs throughout the life cycle of a product or service in the accounting of resources. EEA on the other hand determines cumulative exergy consumption associated with not only raw material inputs but also labor, capital inputs, and non-energetic externalities such as environmental costs (Sciubba 2001; Sciubba 2003).

This thesis uses exergetic efficiency analysis methodology to assess how efficienctly resources are utilized in manufacturing practices (chapter 3). Exergy efficiency of nine major non-renewable construction materials is analyzed in the case study. The study details exergy efficiency of each process steps of a particular production chain introducing theoretical exergy efficiency in order to estimate the improvement potentials.

One of the major shortcomings of exergy analysis is that it focuses only on the process under investigation while ignoring the performance of its production chain in life cycle perspectives. ELCA addresses this shortcoming by determining exergy flows and seeking reduced exergy destructions to improve the efficiency and effectiveness of processes and systems (Dincer and Rosen. 2007). To determine the thermodynamic perfection of a system, not only processes that occur within the system should be considered but also all kinds of interaction between energy and material flows outside the system's boundaries, which enables to evaluate the actual performance of the system and its impact on the environment. The exergy consumption during the complete life cycle allows to evaluate the degree of thermodynamic imperfection of the production processes and to conduct the assessment of the whole process chain associated with the product (Cornelissen 1997).

Life cycle assessment (LCA) is a valuable tool to assess environmental performance, a technique in which the entire life cycle of a product is considered. The environmental impact and efficiency of technologies depend on the characteristics of steps and chains involved over their lifetimes, from natural resource extraction and plant construction to distribution and final product utilization.

ELCA uses the similar framework like LCA, but shows a cumulative loss of exergy due to the generation of entropy. The inventory analysis of the ELCA is more extensive compared to LCA. A complete flowsheet of the mass and energy streams of the different production steps is required, where material and energy balances have to be closed. This is not always the case in a LCA. The exergetic life cycle analysis takes into account destroyed exergy as an impact which is added in classical LCA method. With this approach, resources extracted out of the ecosphere are quantified in terms of exergy. The conversion of the resources into products and waste, and irreversibility can be analysed in exergy terms, showing the role of process efficiency in sustainability (Dewulf and Langenhove 2002). Thus, the main advantage of ELCA is found to be the possibility of giving insight into where the losses occur, and thus to target the processes where improvements can be done. The ELCA can be extended with the abatement exergy of emissions. In normal practice, abatement will be preceded by prevention so that only those emissions that could not be prevented will be abated. In principle the non-zero exergy emission processes can be adjusted to zero-exergy emission processes by separation and transformation of the emissions. This separation and transformation will consume exergy. So an amount of exergy use can be assigned to the different emissions, which can be termed as abatement exergy. By this method the ELCA can be extended to take into account environmental effects associated with emissions and not only depletion of natural resources. An ELCA can also be useful in defining the exergetic payback period for a product or a service. This period can be used, energy systems for instance, as part of a more general assessment including financial aspects (Cornelissen 1997).

Although ELCA can offer promising opportunity in accounting for resource utilizations, its application is still limited, especially within the construction sector. This thesis uses ELCA method in order to assess resource use efficiency throughout the life cycle of PVC and PP as a case study. ELCA is applied not as a substitute of LCA rather an improved option for potential efficiency improvement of the system.

1.2 Objective

The main objective of this thesis is to establish the usefulness and limitations of using material and exergy analysis as a resource accounting tool within the construction sector and to investigate what important role exergy may play in resource metabolism decision-making.The concern has mainly been on saving high valued resources (both material and exergy), and on facilitating the achievement of better sustainability of the construction sector

Specific objectives

Energy intensity of the construction sector in regional economy: Quantify resource (material and energy) inputs, addition to stock, and generation of CDW and their recycling benefits in the Catalan construction sector applying exergy analysis as a resource accounting tool.

Exergy efficiency of construction material manufacturing: Application of exergetic efficiency method to quantify the efficiency of construction material manufacturing, assessing the improvement potentials of processes comparing second law efficiencies in real processes with the theoretical ones.

Exergetic life cycle assessment (ELCA): Assess how efficiently resources are used during the whole life cycle to provide deeper insight into resource use efficiencies and to offer improvement potentials in different stages of a products' life cycle.

CHAPTER 2

Energy intensity of the Catalan construction sector

Barcelona (Source: Google Earth)

Hoque, M. R., X. Gabarrell Durany, C. Sendra Sala, G. Villalba Méndez, L. Talens Peiró, and T. Vicent Huguet. 2012. Energy intensity of the Catalan construction sector: An application of material and exergy flow analysis. *Journal of Industrial Ecology*, *16*(5): 699-709.

A thermodynamic framework is used to characterize the resource consumption of the construction sector in 2001 in Catalonia, the northeast region of Spain. The analysis has been done with a cradle-to-product life cycle approach using material flow analysis (MFA) and exergy accounting methodologies to quantify the total material and energy inputs in the sector. The assessment aims to identify the limitations of resource metabolism in the sector and to pinpoint the opportunities for improved material selection criteria, processing, reuse, and recycling for sustainable resource use. The results obtained from MFA shows that nonrenewables such as minerals and natural rocks, cement and derivatives, ceramics, glass, metals, plastics, paints and other chemicals, electric and lighting products, and bituminous mix products account for more than 98% of the input materials in the construction sector. The exergy analysis quantifies a total 113.1 petajoules (PJ) of exergy inputs in the sector; utilities account for 57% of this exergy.

Besides exergy inputs, construction and demolition waste generation in 2001 is quantified 6.85 million tonnes. With a recycling rate of 6.5%, the sector recovered 1.3 PJ of exergy. If the sector were able to recycle 80% of construction and demolition waste, then exergy recovery would be 10.3 PJ. Hence the results of this analysis indicate that improvements are required in manufacturing processes and recycling activities, especially of energy-intensive materials, in order to reduce the inputs of utilities and the extraction of primary materials from the environment.

2.1 Introduction

The construction sector plays an important role in European economic activities: it is the largest sectoral employer and uses more raw materials than any other sector (EC 2010). The raw materials used are mainly nonenergy minerals, which are non-renewable and have no regeneration rate over a long time (Valero et al. 2010). The increase in construction activities facilitates the depletion of natural resources from the environment and generates large quantities of waste in different phases of the construction process: extraction, manufacture of materials, construction itself, demolition, and finally disposal. Therefore, one of the major drivers of economic growth is the increase in consumption of natural resources. But sustainability objectives demand reduced resource consumption, especially of non-renewable resources. Increases in consumption levels require potential efficiency improvements for both production and consumption; industrial ecology provides the tools to pinpoint the limitations of resource use efficiency. Focusing on material and energy consumption in the construction sector in a regional economy, this study highlights the key results obtained from the application of material flow analysis (MFA) and exergy accounting methodologies.

MFA is used to identify and quantify the consumption of natural resources associated with economic evolution from a biophysical point of view and based on the mass balance principle. In the past two decades, MFA has been applied on the national (Carlsson et al. 2008; Cañellas et al. 2004), cross-country (Adriaanse et al. 1997; Eurostat 2001; Weisz et al. 2006), regional (Kovanda et al. 2009; McEvoy et al. 2004), city (Tanikawa and Hashimoto 2009), and industrial or sectoral levels (Bringezu and Schutz 1997; Hashimoto et al. 2007; Mutha et al. 2006; Sendra et al. 2007; Tanimoto et al. 2010) in order to quantify material use within specified boundaries. In addition to MFA, exergy accounting is a rapidly evolving approach with respect to process analysis and resource accounting (Dewulf et al. 2007). The law of mass/energy conservation is based on the fundamental physical principle that neither matter nor energy can be created or destroyed (except in nuclear reaction, when mass and energy are interconvertible). However, resource consumption in real industrial processes is analogous to the degradation of quality, which is equivalent to the amount of entropy generation or exergy loss. Thus the exergy concept implies an entropy-free energy form that can be perceived as a measure of usefulness. Exergy can be applied as an indicator using a life cycle perspective that considers all the inputs from natural resources to obtain a final product. Such exergy accounting is called cumulative exergy consumption (CE_xC) and represents the sum of the exergy of the material and energy consumed in the production chain to produce the final product (Szargut et al. 1988). Exergy accounting found its applications in terms of resource accounting (Szargut et al. 1988), on the process level (Costa et al. 2001; Talens et al. 2007; Wall 1988), sector level (Masini et al. 2001), and national level (Ertesvåg 2001; Gasparatos et al. 2009). The concept also raised interest in mineral resource accounting (Bösch et al. 2007; Valero Delgado 2008; Dewulf et al. 2007; Meester et al. 2006; Valero et al. 2010), waste management (Talens Peiro et al. 2008), exergetic life cycle assessment in the built environment (Meester et al. 2008), and extended exergy accounting (Sciubba 2001; Sciubba 2003; Talens Peiró et al. 2010).

The objective of this analysis is to use exergy as a resource accounting tool and to quantify the exergy use of the construction sector. This will provide necessary information for identifying the potential limitations of resource use and pinpointing opportunities for improved material selection criteria, processing, and potential for reuse and recycling. This study uses exergy as an indicator to provide a better understanding of the total material and energy requirements of the construction sector. It also identifies which materials represent the highest CE_xC and thereby contribute most to the total resource use of the sector. One of the major advantages of exergy accounting is that this concept provides an estimation of the minimum theoretical resource requirement (material and energy) of a process, representing the maximum savings that can be achieved (Dincer et al. 2004). Consequently the exergy concept provides a better foundation for improvement and for calculating expected savings of natural resources.

2.2 Catalan construction sector

Catalonia is one of the 17 autonomous communities of Spain, situated in the northeast of the country. It borders France and Andorra to the north, Aragon to the west, the Valencian community to the south, and the Mediterranean Sea to the east. Table 2.1 provides a comparative overview of the main structural and economic indicators of Catalonia, Spain, and the European Union-15 (EU-15) countries[5]. The data show that

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[5] EU-15 countries are the 15 member states of the European Union (EU) before the enlargement on 1 May 2004. These 15 countries include Belgium, France, The Netherlands, Germany, Italy, Luxembourg, Denmark, Ireland, the United Kingdom, Greece, Portugal, Spain, Austria, Finland, and Sweden.

Catalonia is a densely populated region with higher economic activity than Spain generally; it is similar to other EU-15 countries. The region occupies only 6% of Spanish territory, but primary energy consumption and gross domestic product (GDP) at market price are 19% and 20% of the Spanish total, respectively. Gross value added (GVA) of the construction sector (8.2%) in the Catalan economy is similar to the sector across the Spanish economy (9.5%), but much higher than the EU-15 average (5.4%). Thus, Catalonia has specific importance in the Spanish economy, both by geographical location and economic activity. In addition, a regional emphasis has become more important since the late 1990s, when Spanish regions gained greater political autonomy. It is much easier for decision makers to influence regional or local-level consumption patterns or management practices than those at a broader level. A regional focus is also relevant because bulk quantities of construction material are produced in the region.

Table 2.1: Socio-economic indicators of Catalonia, Spain, and the EU-15.

Indicator	*Catalonia*			*Spain*			*EU-15*		
	2001	*2007*	*2011*	*2001*	*2007*	*2011*	*2001*	*2007*	*2011*
Area (km^2)		32,106.5			505,997.0			3,315,793.0	
Population (1000)	6,361.4	7,210.5	7,519.8	41,116.8	45,200.7	46,815.9	379,688	393,178	399,418
Population density (inhabitants/ km^2)	198	225	234	81	89	93	115	119	120
GDP (million €)	135,709	214,714	215,181	680,678	1,053,537	1,063,355	9,094,927	11,525,434	11,648,895
GDP per capita (€/ inhabitant)	21,333	29,778	28,615	16,555	23,308	22,714	23,954	29,314	29,165
GVA of construction sector (%)	7.1	9.5	7.5	8.1	10.6	9.3	5.1	5.6	5.4
Energy consumption (ktoe)	24,030.8	26,840.2	24,297*	127,930	146,779	129,339	1,501,864	1,526,960	1,549,117
Energy use per capita (toe/ inhabitant)	3.78	3.72	3.5*	3.11	3.15	2.76	3.96	3.88	3.88
Energy consumption per area (toe/km^2)	748.5	836.0	756.8	252.8	290.1	255.6	452.9	460.5	467.2

*Note: km^2 = square kilometers; GVA = gross value added; ktoe = kilotonne oil equivalent; toe = tonne oil equivalent. One square kilometer (km^2, SI) = 100 hectares (ha) ≈ 0.386 square miles ≈ 247 acres. One metric ton (t) = 10^3 kilograms (kg, SI) ≈ 1.102 short tons. Tonne of oil equivalent (toe) = 41.87 × 109 joules; one ktoe = 1000 toe. Source: Eurostat; IDESCAT; INE. *2010 data.*

House ownership in Catalonia is greater than 80% and ownership of second houses reached 14% in 2001; thus, building construction can be used as an indicator to demonstrate the construction trend of the region. Cement consumption can also be used as a key criterion to represent the construction trends, not only for buildings, but also for infrastructure. As shown in figure 2.1, cement consumption and construction of new buildings increased each year, nearly doubling from 32,237 units in 1995 to 62,556 units in 2002 (IDESCAT 2009), then reaching a saturation level (except for an increase in cement consumption in 2006 and 2007). This increase was mainly due to the construction of a new airport and high-speed railway facilities. A moderate growth of roadways was noticed, only 9% in 15 years, from 11,203 kilometers (km) of roadway in 1990 to just over 12,177 km in 2004 (INE 2010)[6]. The year 2001 represents the construction sector at its peak; establishing important baselines in terms of waste might be expected over the following years.

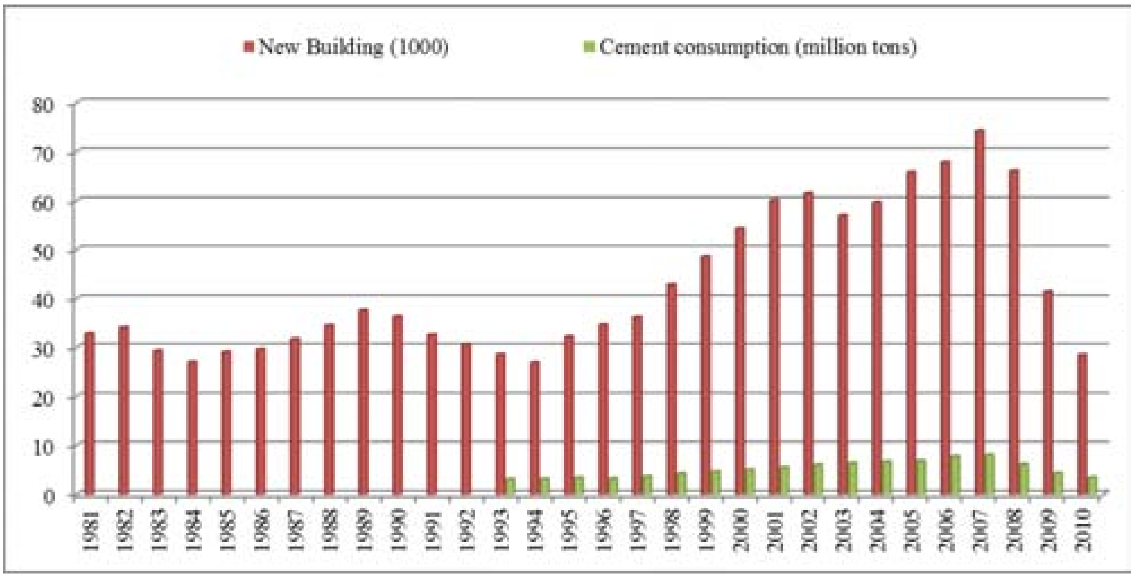

Figure 2.1: New building construction and cement consumption in Catalonia, 1981-2010. Cement consumption data is not available for Catalonia prior to 1993. *Data Source:* Institut d'Estadística de Catalunya. T = metric ton.

A lack of accurate data is historically a major hindrance in regional resource accounting of the construction sector; however, this problem was addressed in 2000 by the official

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[6] One kilometer (km, SI) ≈ 0.621 miles (mi).

statistics Web site of Catalonia (Institut d'Estadística de Catalunya [IDESCAT]) of the Generalitat de Catalunya, the regional government of Catalonia.

Growth of the construction industry in Catalonia has precipitated a noticeable increase in the generation of construction and demolition waste (CDW). Reuse and recycling of CDW in Catalonia is still far behind average practices of the EU-15. In 2001, Catalonia had a recycling rate of 6.5% (ARC 2009), well below countries like Belgium, Denmark, and the Netherlands (81% to 90%) (Symonds 1999). There is an overall deficiency in the application of appropriate waste management practices by construction companies in Catalonia. Given the current situation in the Catalan construction industry, with its high level of activity both in building and civil works, the region could easily absorb more recycled waste materials.

2.3 Methods

In order to quantify the material and energy flows of the construction sector, it is necessary to identify the types of construction and material categories. The types of construction included in this study are buildings and infrastructure (see table A.3 in the Appendix A for more details on contruction tupes); materials included are those defined in the report entitled, “The construction industry mass balance: Resource use, wastes and emissions” (Smith et al. 2003), along with other materials deemed necessary (see table A.4 in Appendix A for a complete list of materials). All the materials are devided into 11 categories by origin and characteristics. The categories are minerals, natural rocks, ceramics, cement and cement derivatives, glass, asphalt and bituminous mix products, wood, chemicals, plastics, metals, and electric and lighting products. The economy-wide MFA analyzes the system as a black box without considering the interactions among the subsystems. However, in this analysis those interactions are taken into consideration to avoid double counting, as some of the flows are interconnected (e.g., minerals are used as raw materials to produce cement and derivatives, ceramics, and glass). Figure 2.2 illustrates the flows and activities of the construction sector, demonstrating the interactions of materials with the foreign market and natural environment. Material and energy flows are analyzed through a cradle-to-product life cycle perspective; thus energy consumption during construction activities and utility phases is excluded from this study.

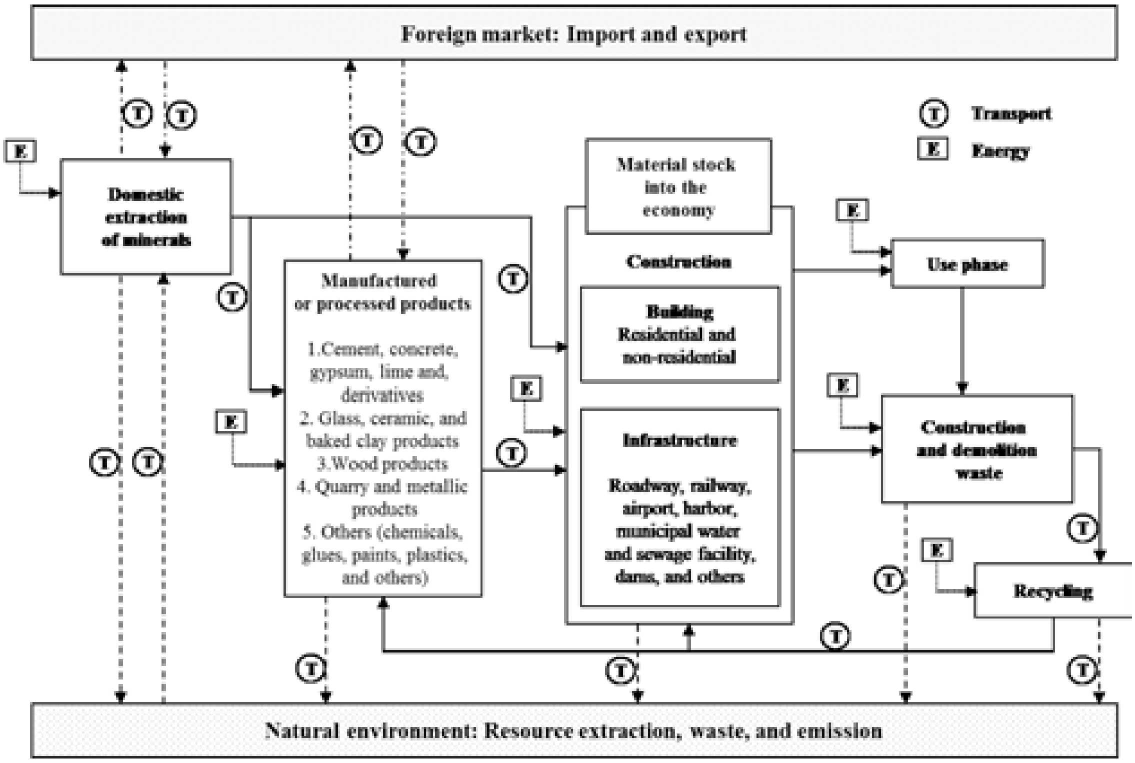

Figure 2.2: Material inflows and outflows of the construction sector, including energy and transport through different construction activity phases. Waste generated during use phase, due to renovation and maintenance, is considered as CDW. Solid lines represent material movement within the sector; dotted lines represent energy use in different activity phases, partly embodied in materials and the rest dissipated to the environment; dashed lines represent material interaction with the natural environment; and unevenly dashed lines represent material imports and exports.

Reserves of construction minerals and raw materials are limited; thus reuse and recycling have potentials to reduce resource extraction from nature and to reduce energy demand in the production process. For instance, recent research shows that high-grade bauxite reserves are declining, and thus aluminum production may become uneconomical as the exergy use for processing low-grade bauxite grows much higher (CSIRO 2010). The reuse and recycling benefits of aluminum structures are twofold: (i) providing an alternative way to obtain high-quality aluminum and (ii) reducing the resource used for its production. When considering reuse and recycling, exergy can be used to assess the potential benefits of material recycling and its recycling efficiency. The recycling potential can be estimated by comparing the recoverable exergy embodied in the material with the CE_xC used to produce the material. At the process level, exergy can account for the outputs of the system (e.g., emissions, wastes, and heat losses) with an exergy balance of the process. This provides necessary information to improve process efficiencies.

Energy intensity was measured from the total exergy required per unit output or activity. This required exergy is the sum of all exergy inputs (materials and utilities) from a cradle-to-product life cycle perspective. Exergy of utilities includes the exergy required for extraction, production, and transportation.

1.2.1 Material flows

The MFA of construction materials was conducted considering the inputs and outputs of the system explained in economy-wide MFA (Eurostat 2001). Apparent consumption of materials was quantified based on equation 2.1:

$$\text{Apparent consumption} = \text{Extraction} + \text{Production} + \text{Import} - \text{Export} \qquad (2.1)$$

where extraction is the domestically extracted minerals used directly in the construction activities excluding those used as raw materials to produce other construction materials[7]. Mineral extraction, production, imports, exports, CDW, and transport data were adopted from Catalan and Spanish official statistical databases (II PNRCD 2007-2015, EM 2001, GENCAT 2009, IDESCAT 2001, IDESCAT 2009, INE 2010, and Ministerio de Fomento 2001). See table A.5 in the Appendix A for a complete list of data sources.

1.2.2 Exergy flows

The chemical exergy of inorganic materials depends on the chemical species and mineralogical composition. Mineral compositions are difficult to define precisely, as they vary considerably depending on their origin and geographical location. Compositions were estimated for materials in the case of unavailable literature data. The chemical exergy of wood products was calculated using the method proposed by Szargut and colleagues (1988) (see appendix A). The chemical exergy of plastic products was calculated by using two different methodologies: (i) calculating the β values of hydrocarbons and (ii) by group contribution as proposed by Szargut and colleagues (1988). Data for mineral compositions and manufacturing processes were adopted from published literature (Ayres and Ayres 1999; Bösch et al. 2007; Dewulf et al. 2007; Federici et al. 2008; Koroneos and Dompros

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[7] Direct use is defined as the use of minerals in construction with or without minimal processing after extraction, for example, sand or crushed stone used in road construction. Indirect use includes all the minerals processed in an industry to produce either semi-finished or finished products, for example, limestone to produce cement.

2007; Marabini et al. 1998; Michaelis et al. 1998; Nicoletti et al. 2002; Schmitz et al. 2011, Ecoinvent 2007, the Energy Research Centre of the Netherlands (ECN 2009), the European Integrated Pollution Prevention and Control Bureau (IPPC 2010), and IDESCAT 2009 (see table A.6 in the Appendix A for a complete list of data sources).

The modes of material movement were mainly by road transport, and the transport distance was calculated between the centers of different counties. Foreign trade distance was calculated between Barcelona and the capitals of the importing or exporting countries. Railway transport within the Spanish states and air freight were minimal in 2001 and were omitted due to lack of information. An average transport distance of 500 km accounted for maritime traffic of goods within Spanish territories. Fuel consumption associated with the transportation of goods, both for domestic and foreign trade, used coefficients from the Ecoinvent v2.0 database (Ecoinvent 2007).

2.4 Results and discussion

The construction industry accounts for more than 90% of nonenergy mineral consumption, and, of this, one-third is used in road construction. Other uses include buildings and other infrastructure, as well as the manufacture of cement, lime, plaster, and a variety of other products like glass and ceramics (McEvoy et al. 2004). Analyzing all the mineral data, figure 2.3 illustrates a comprehensive mass balance flow diagram of construction minerals for Catalonia in 2001. This diagram indicates some of the important issues facing the Catalan construction sector. The domestic extraction (DE) of minerals in the region was 76.3 million tonnes, and apparent consumption was 57 million tonnes, representing nearly 75% of the total extraction[8]. Figure 2.3 shows that 37.9 million tonnes of minerals were used as precursors to produce other materials, and 18.8 million tonnes were used directly in the sector. A majority of these precursors (23.1 million tonnes) were used to manufacture concrete, mortar, and derivatives; nearly 11.0 million tonnes were used in cement production, and the remaining 3.8 million tonnes were used to produce ceramics, glass, lime, gypsum, and other relevant construction products. Catalonia does not depend on imports for minerals (EM 2001), which is a reason for this region to optimize resource consumption in all life cycle stages of this sector.

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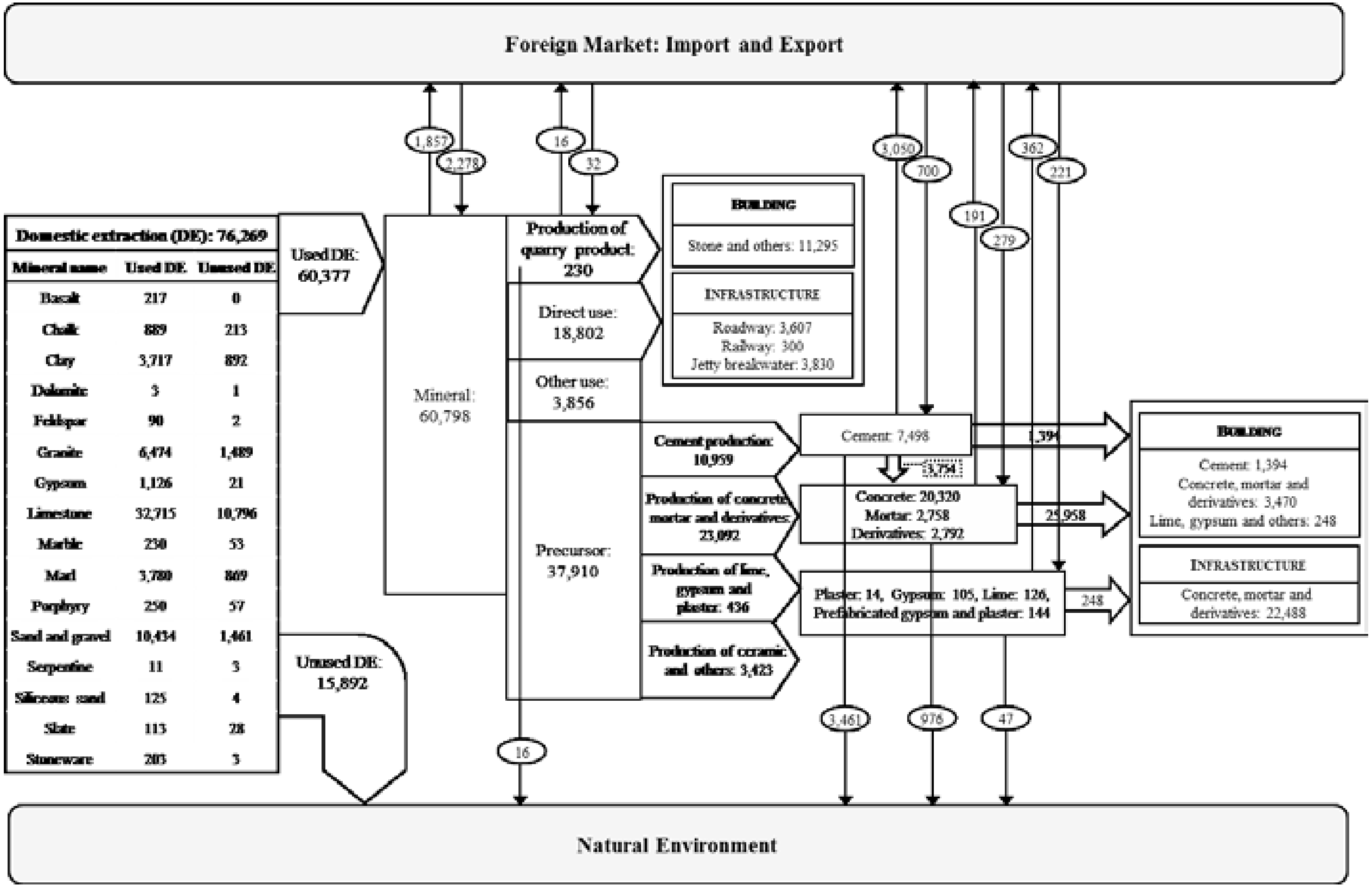
[8] Throughout this study, “tonnes” refers to metric tons. One metric ton (t) = 10^3 kilograms (kg, SI) ≈ 1.102 short tons.



Domestic extraction (DE): 76,269

Mineral name	Used DE	Unused DE
Basalt	217	0
Chalk	889	213
Clay	3,717	892
Dolomite	3	1
Feldspar	90	2
Granite	6,474	1,489
Gypsum	1,126	21
Limestone	32,715	10,796
Marble	230	53
Marl	3,780	869
Porphyry	250	57
Sand and gravel	10,434	1,461
Serpentine	11	3
Siliceous sand	125	4
Slate	113	28
Stoneware	203	3

Figure 2.3: Mass balance flow diagram of construction minerals in 2001 in Catalonia. All numbers are in kilotonnes.

In 2001 the consumption of material in the construction sector totaled 55.5 million tonnes. Nearly 36.7 million tonnes were processed materials. Among all the processed materials, cement and cement derivatives accounted for 27.6 million tonnes; ceramics 4.4 million tonnes; asphalt and bituminous mix products more than 1.9 million tonnes; and wood, metal, plastic, chemical, and electric and lighting products accounted for the remaining 2.8 million tonnes. Nonmetallic minerals and mineral-processed materials accounted for more than 92% of the construction materials (figure 2.4). Therefore care must be taken while planning for provision of both pre- and post-construction, as mineral resources are finite.

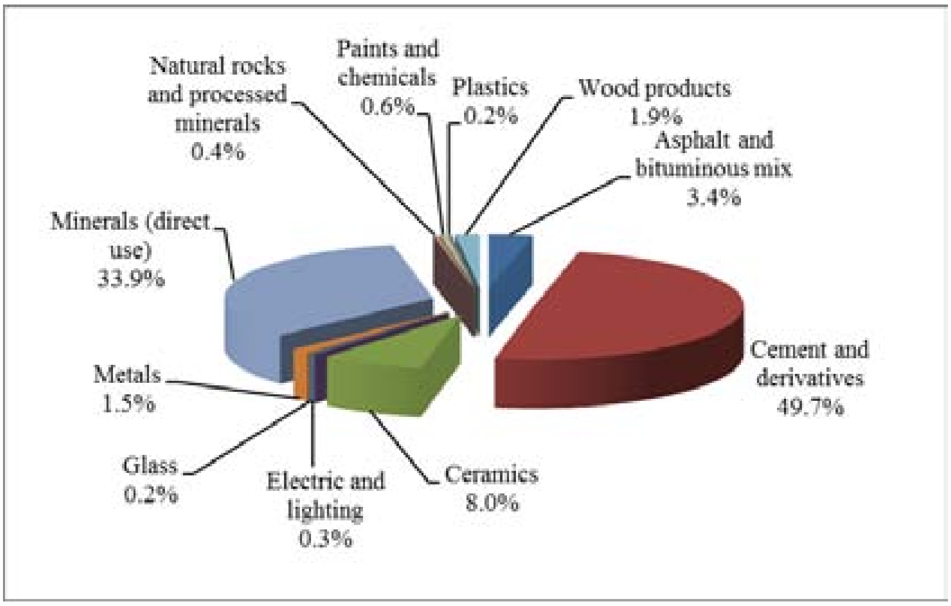


Figure 2.4: Percentage by different materials of total consumption in the Catalan construction sector in 2001.

Building construction uses diversified material categories, whereas infrastructure mainly uses aggregates, concrete, metal, and bituminous products. While analyzing the destinations of materials it was found that approximately 41% was used either in new building construction or in renovation activities, and the remaining 59% were used in infrastructure. Catalonia has a scarcity of metal ores and imports metallic raw materials and finished products. The total consumption of metallic products was nearly 0.9 million tonnes, with 80% of these products either iron or steel. One of the main advantages of metallic products is greater recyclability. Quantifying paints, chemical products, and electric and lighting products was difficult due to the great variety of product types and origins. The total consumption of paint and chemical products was more than 0.3 million tonnes, with 66% of these products being paints and varnishes.

In 2001 the construction sector generated 6.85 million tonnes of CDW, of which 0.45 million tonnes was recycled. The remaining 6.4 million tonnes was sent to landfill. It was difficult to distinguish which waste materials were recycled or reused, as there was no precise information available on the composition of CDW. An estimated composition of CDW was published in Spain (PNRCD 2001, 2006) and was adopted in this analysis to quantify different types of waste materials (see table A.7 in Appendix A).

The chemical exergy data of minerals are available in literature and were adopted in this analysis (see table A.8 in Appendix A). The extraction processes required an average 0.03 gigajoules (GJ) of exergy per tonne of mineral extracted[9]. Estimated chemical exergy values of manufactured materials are provided in table 2.2, which illustrates that chemical exergy of processed materials from minerals is lowest among all manufactured materials. However, these materials are used in large quantities in construction and are not easily recyclable, thus postconstruction impacts of these products are relatively high compared to easily recyclable materials like metals, wood products, or plastics.

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[9] One gigajoule (GJ) = 10^9 joules (J, SI) ≈ 2.39×10^5 kilocalories (kcal) ≈ 9.48×10^5 British thermal units (BTU).

Table 2.2: Chemical exergy and process exergy demand for manufactured materials.

Material name	*Chemical exergy (GJ/t)*	*Process exergy (GJ/t)*	*Material name*	*Chemical exergy (GJ/t)*	*Process exergy (GJ/t)*
Paving slab	0.19	0.07	Cement	0.53	4.2
Sanitary ceramic	0.80	21.72	Gypsum plasterboard	0.29	1.69
Ceramic brick	0.83	2.44	Gypsum panel	1.35	1.66
Ceramic tile	0.72	5.9	Concrete	0.14	0.65
Glass fibre	0.83	9.0	Mortar	0.19	0.65
Flat glass	0.98	6.12	Asphalt and bituminous mix products	2.29	0.54
Railroad sleeper	19.45	3.50	Iron and Steel	6.75	18.80
Plywood	19.97	5.45	Aluminum (primary)	32.80	105.60
Waste wood	17.94	0.36	Copper	2.11	32.05
Particle board	20.24	5.45	Shuttering wood	19.60	0.36
Hard board	20.18	5.45	Sawdust	20.43	0.37
Soft board	20.05	5.45	Wood door	20.21	0.36
PVC (Polyvinyl chloride)	19.32	33.95	ABS (Acrylonitrile, Butadiene, Styrene)	41.68	34.41
High density Polyethylene (HDPE)	41.87	34.32	Low density Polyethylene (LDPE)	44.88	39.66
Polypropylene	46.20	32.95	Polystyrene	44.67	51.48

Note: GJ/t = gigajoules per metric ton. See tables A.9 and A.10 in the Appendix A for more details.

The consumption of wood products represents a small fraction in terms of mass; however, in terms of chemical exergy content and exergy use in manufacturing processes, wood is an energy-intensive material. The traditional construction in Spain is based on the use of heavy masonry, but wood construction is 14% lower in life cycle embodied energy than a concrete and superinsulated construction over a 100-year period (Gonzalez and Navarro 2006). Because of renewability and recyclability, wood can be a better choice of construction material, although the sector depends on imports for these products. Cement production requires high exergy input in its production chain, nearly 4.2 GJ/t (Ciment Catala 2009). Increasing use of secondary materials in cement manufacturing, such as fly ash or blast furnace slag, and alternative fuels like waste oil and forest residues, will reduce the primary resource consumption in the sector[10]. Besides, exergy of the secondary material is considered to be recovered exergy. CDW has a high recovery potential: more than 80% of the wastes can be recycled or reused, although the recycling rate was approximately 6.5% in Catalonia in 2001 (ARC 2009). Exergy recovery from CDW was assedded by assuming metals, asphalt and bituminous mix products, glass, and aggregates were mainly recycled and recirculated in the sector. The estimation found that the recovery was 1.3 petajoules (PJ), whereas with improved management practices, the recovery could be 10.3 PJ, or eight times higher than the actual recovered value[11].

The exergy balance flow chart (figure 2.5) shows that the overall exergy input in the sector was 113.1 PJ, with chemical exergy of materials representing 48.5 PJ and the remaining 64.6 PJ from exergy of utilities. Apart from exergy inputs, addition to stock accounted for 40.3 PJ of exergy, which is nearly 36% of the total exergy input in the sector. It was also estimated that 0.7 PJ of exergy was recovered from construction waste, and the remaining 7.5 PJ of exergy was sent to the landfill site; thus a total 72.1 PJ of input exergy was lost from the system.

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[10] Secondary materials are defined as the waste from other manufacturing processes such as slag (produced from pig iron production) or fly ash (produced from hard coal power plants).

[11] One petajoule (PJ) = 10^{15} joules (J, SI) ≈ 9.48×10^{11} British thermal units (BTU).

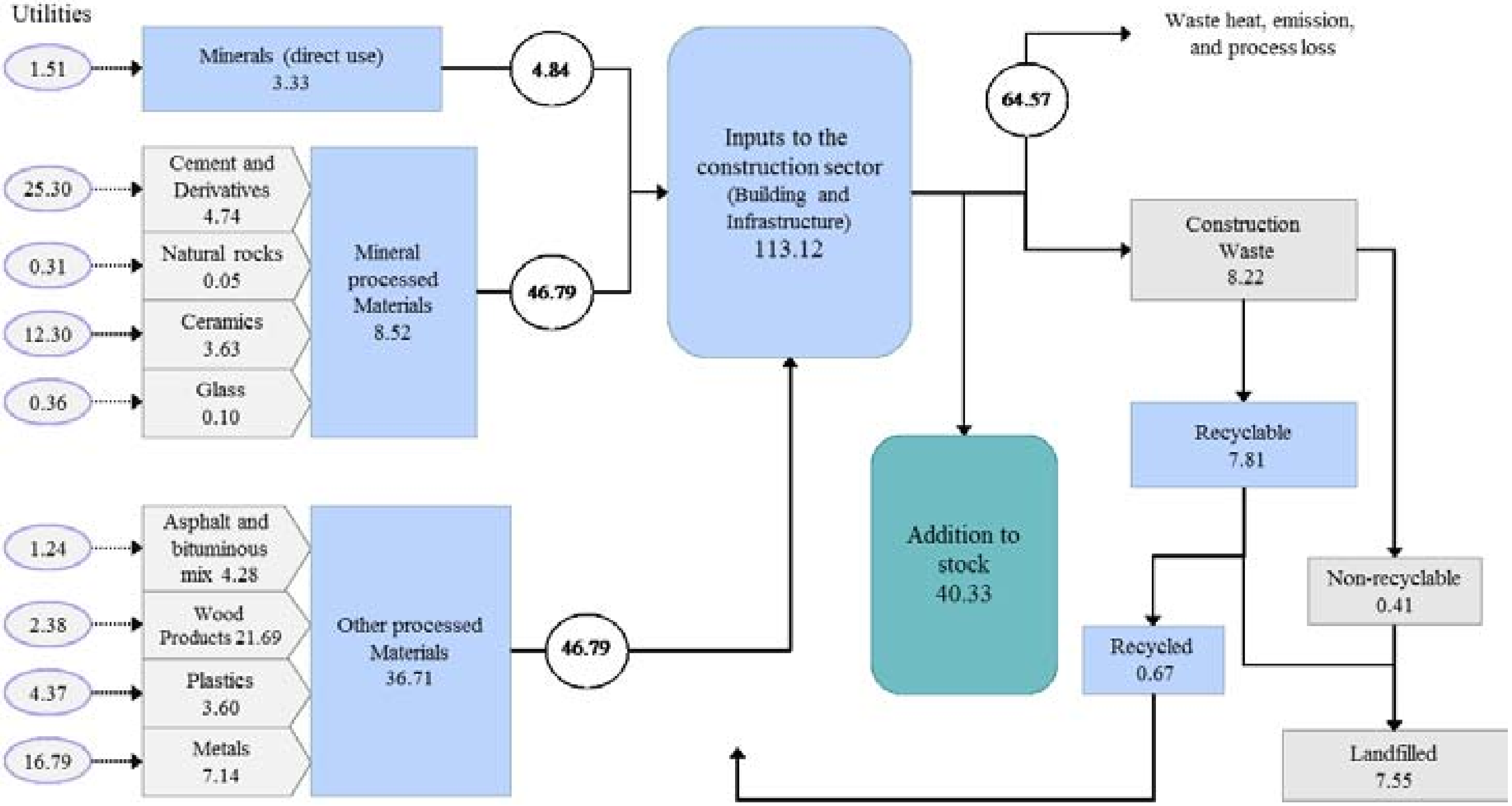


Figure 2.5: Exergy balance flow chart of the 2001 Catalan construction sector in petajoules.

An accurate life span of buildings and infrastructures was difficult to determine, but was estimated for Catalonia at 75 and 30 years, respectively (Maña i Reixach et al. 2000). After the life span of buildings and infrastructure, these stocks will be converted to waste. Proper management practices will therefore facilitate the recovery of exergy, which in turn will provide efficient resource use in this sector.

Of the materials studied in this analysis, aluminum was found to be the most energy-intensive material, with a chemical exergy of 32.8 GJ/t, and process exergy demand of 105.6 GJ/t for primary aluminum production. Energy-intensive materials such as plastics, wood products, metals, ceramic, glass, and bituminous mix products accounted for 77.9 PJ of exergy, or 69% of the total exergy input, although these materials represented only 15% by mass. This is because of the higher chemical exergy content of these materials and higher exergy demand in their manufacturing processes. Energy intensity of different materials in terms of chemical exergy and exergy of utilities is illustrated in figure 2.6. Comparing values, it can be concluded that plastics are the most energy-intensive material, with an average intensity of 77 GJ/t. Chemical exergy can be recovered partially or completely after the life cycle period of buildings and infrastructure through recycling of the used products; however, exergy of utilities is mostly lost during the process steps. In this context, greater sustainability can be achieved by increasing process efficiency and reducing exergy loss during the production phases. In addition, increasing the use of materials with higher recyclability will reduce the exergy inputs in the manufacturing processes and will facilitate dematerialization of this sector.

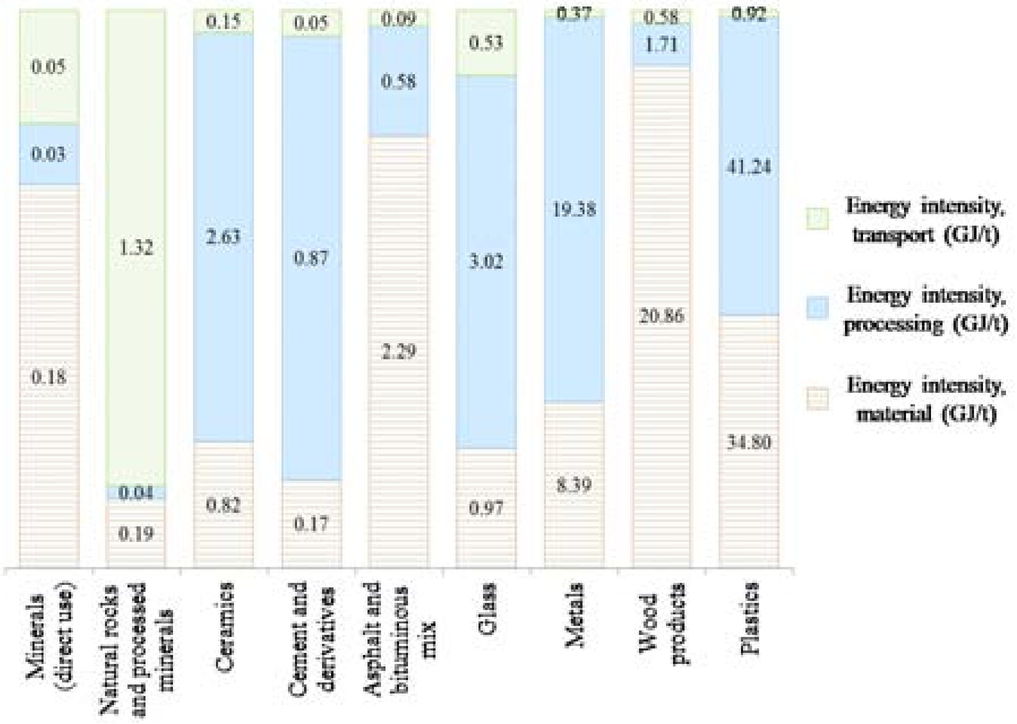


Figure 2.6: Energy intensity of construction materials in terms of chemical exergy and exergy for utilities. Note that cumulative exergy is not equal across materials.

It is evident from figure 2.6 that materials with higher energy intensity relative to sectoral intensity estimated for the year 2001 (2.04 GJ/t) are more easily recycled than those with lower energy intensity. Thus energy-intensive materials should be prioritized to increase their use in the construction sector, as these materials can be recirculated in the system after end-of-life. The recycling benefits of all CDW may not always be positive, as with some polymers that are difficult to bring back to their original monomer; however, these can be used as an energy source in cement kilns, which is still not the case in Catalonia.

Recycling materials are also always contaminated to some degree. The presence of contaminants in the recycling stream causes a shift in the original composition of the materials being recycled. Consequently the quality decreases with each recycling step (Amini et al. 2007). On the other hand, recycling contributes significantly to the preservation of natural resources, such as energy and primary materials, and to the decreased environmental impact of primary resource exploitation (Ignatenko et al. 2007). As an example, steel production from primary raw materials and the recycling of steel scrap has been calculated to evaluate the recycling benefits available from recycling. The results obtained from this case study show that primary steel production, steel production using 48% scrap, and scrap recycling in electric arc furnaces require 38.0 GJ, 23.9 GJ, and 16.3 GJ of exergy input, respectively, in order to produce 1 tonne of steel. The results demonstrate that steel produced from a scrap recycling process consumes much less material and energy during the whole recycling chain. (see table A.11 in Appendix A for more details.) This sample estimation provides insight to improve the overall process efficiency and to use more recyclable materials in production processes.

The energy intensity of construction materials showed why exergy analysis was preferable together with MFA. MFA provides insight into the resource inputs and outputs, whereas exergy analysis determines the changes in exergy of resources throughout the life cycle. The results obtained from this analysis can be used as a primary resource for practitioners and policy makers in meeting future strategies of material selection. For example, consumption of wood products in the Catalan construction sector is minimal compared to average uses in the EU-15 countries. Wood incorporates more renewable exergy and can substitute for cementitious materials, reducing the depletion of finite resources. Besides, the exergy of wood products can be partially or completely recovered after a life cycle period.

2.5 Limitations of the analysis in exergy accounting

Inadequate data sources for construction materials made it difficult to quantify the exergy flows in the construction sector. It is necessary to identify the origins, extraction, manufacturing processes, modes of transport, and activities associated with the scope of the study to gain a precise result from the analysis. Exergy use for machinery production was not included in this study because the impacts were considered negligible due to the long life span of the machinery. Energy consumption of biomass extraction from the forest was estimated for Catalonia by Martinez Gasol and colleagues (2009). Based on this estimation, this study found that the extraction process accounted for 0.002% of the total exergy consumed to produce the final product. Regional manufacturing process data on metallic product manufacturing were not available. Metal industry data are adopted from Ayres and Ayres (1999) and Masini and colleagues (2001). Due to data unavailability, paint and lighting materials are excluded from exergy accounting. These excluded materials represent 0.9% of the total material input to the sector, and some of these materials are energy-intensive because of their organic and metallic origin.

Therefore excluding these materials from exergy accounting does not allow to quantify the accurate exergy input to the construction sector.

2.6 Conclusion

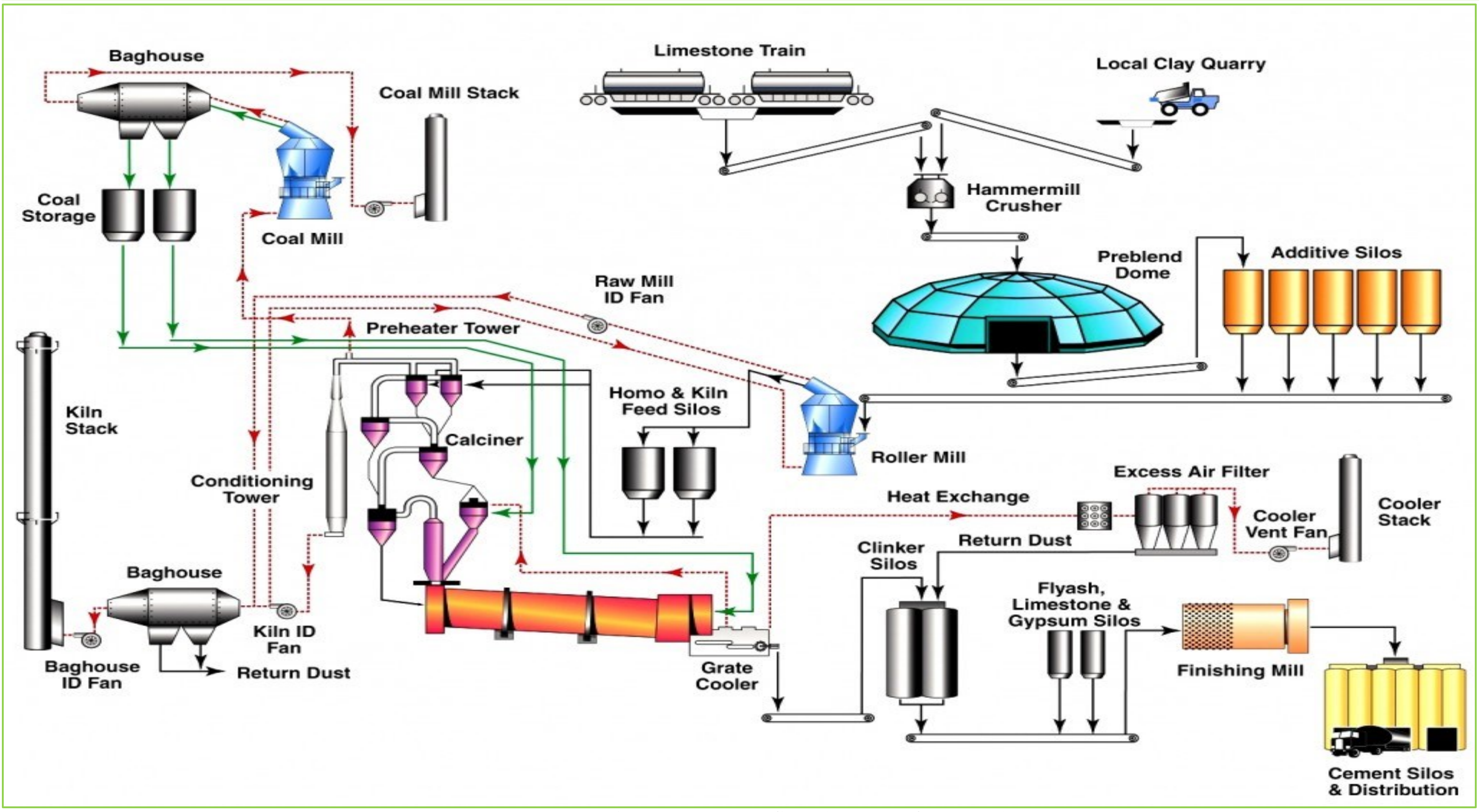
This study characterizes the resource consumption patterns of the Catalan construction sector in 2001 using MFA and exergy accounting methodologies. The analysis was done with a cradle-to-product life cycle approach to quantify the total material and energy inputs in the construction sector. The results obtained from MFA showed that the total material input in the sector was 55.5 million tonnes, and more than 98% of these materials were nonrenewable resources. The sector generated a total of 6.85 million tonnes of CDW in 2001, and only 0.45 million tonnes was recycled or recirculated in the sector. Therefore, continuing construction activities and low recycling rates of CDW are depleting the finite, and nonrenewable, natural resources. The exergy analysis showed that the total exergy input in the construction sector was 113.1 PJ, with chemical exergy representing 48.5 PJ and the remaining 64.6 PJ from exergy of utilities. The analysis highlights that energy-intensive materials have higher chemical exergy and require higher exergy inputs in their manufacturing processes. The energy-intensive materials such as metal, plastic, wood, glass, ceramic, and bituminous products accounted for 77.9 PJ of exergy, which is 69% of the total exergy input in the sector, though these materials represented only 15% of the total material input in terms of mass. Hence improvements in manufacturing processes of energy-intensive materials would contribute to optimization of resource use efficiency. The analysis also showed that, with present recycling rates of 6.5% of CDW, 1.3 PJ of exergy were recovered from this sector. If the sector recycled 80% of CDW instead of sending it to landfill, the exergy recovery could be 10.3 PJ. Thus CDW should be prioritized for reuse and recycling, especially energy-intensive materials, at least from an energy conservation perspective. The results of this study therefore showed that exergy analysis together with MFA offers a comprehensive evaluation of resource consumption in the construction sector and therefore can be useful in meeting future strategies in this sector.

This study detailed some of the main limitations of resource use related to the flows of material and energy, providing possible quantifications. Although this was a case study of the Catalan construction sector, the findings also have relevance to other regions. It is suggested that the construction sector should focus on increasing the use of materials with higher recyclability; these materials could be recirculated in the system, which in turn will reduce the primary resource inputs in the economy. It appears from the results that utilities accounted for 57% of the total exergy inputs; therefore, quantification of the minimum exergy requirement in the manufacturing process will provide deeper insights and guidelines to improve technologies for material management and manufacturing processes.

Supporting Information (Appendix A): This supporting information provides descriptions of chemical exergy calculations, calculations of β values for wood products, exergy calculations of plastic products from β values and group contribution, and additional information about the data used in the case study analyses.

CHAPTER 3

Exergy efficiency of material manufacturing



Cement production process flow (Source: fpaci.org)

Hoque, M. R., G. Villalba Méndez, X. Gabarrell Durany, and C. Sendra Sala. 2012. Exergetic efficiency analysis of construction material manufacturing. *Submitted to International Journal of Exergy (June 2013).*

This study presents the use of exergetic efficiency analysis in order to assess how efficiently resources are utilized in present industrial processes. The role of exergy is discussed from several key perspectives such as quality, energy conservation, and process improvement potentials. Both primary and secondary production processes of eight major non-renewable construction materials (steel, aluminum, copper, cement, concrete, ceramic, glass, and polyvinylchloride) have been analyzed in this study. Theoretical exergy efficiency approach is outlined to quantify the improvement potentials of present manufacturing processes.

The large difference between theoretical and practical exergy demand suggests that exergy resources are utilized very inefficiently in current technologies. It is found from this analysis that more than 55% of exergy is being lost in current technologies even though a significant amount of waste heat is recovered. Thus, a more emphasize is required on the reduction of specific exergy losses as the result of improved process design and introduction of new technology. The results also show that secondary process has a great potential to achieve an efficient industrial sector since average exergy loss in secondary process (30%) of the case study materials is far lower compared to primary process (62%).

3.1 Introduction

The manufacturing sector uses enormous amounts of material and energy resources, much of which is wasted due to process inefficiency. As a result, resource use optimisation has become more and more important, particularly in the manufacturing sector. Industrial ecology concept promotes the shifting of industrial processes from open loop to a closed loop system, where wastes become inputs for new processes in order to achieve sustainability of the industrial system (Ayres 1989). The useful output from a process step becomes the input for the succeeding step until a final product is produced. Each of these steps generates entropy and material waste. In conventional energy analysis, based on the first law of thermodynamics, the loss of energy quality is not taken into account (Rosen 2004). For example, the quality change of thermal energy from a higher to a lower temperature cannot be established in an energy analysis as the entropy generation is not taken into consideration it shows the energy flow to be continuous (Cornelissen 1997). Exergy analysis on the other hand, based on the first and second law of thermodynamics, illustrates the thermodynamic inefficiency of a process, including all quality losses of energy and materials (Branham et al. 2008). Therefore, a better measure of resource use efficiency can be assessed by using exergy analysis to analyse manufacturing processes.

The concept of exergy also provides an estimation of theoretical minimum resource requirement (energy and material) of a process, providing information on the maximum savings that can be achieved from it (Dincer et al. 2004). Exergy calculations can therefore provide enhanced understanding of a process quantifying its improvement potentials.

Thermodynamic analysis has been undertaken in a number of studies to analyse the manufacturing processes of cement and clinker, chemical, metal, and plastic (Ayres et al. 2011; Ayres et al. 2006; Ayres and Ayres 1999; Ayres et al. 1981; Balomenos et al. 2011; Dewulf and Van Langenhove 2004; Gyftopoulos et al. 1974; Hedman et al. 1980; Kolip and Savas 2010; Koroneos et al. 2005; Michaelis et al. 1998; Szargut et al. 1988; Wall 1988). These studies presented exergy accounting for individual process or process stages, in order to identify major losses and evaluate the potentials for further technical improvements. The results obtained from different stages of the overall process are not typically combined to give an overall efficiency representation from exergy perspective.

Without such an approach it is hardly possible to evaluate the resource use efficiency and environmental burdens associated with the consumption of materials in construction applications.

This study uses exergetic efficiency analysis tool in order to estimate the process improvement potentials of construction material manufacturing. Theoretical exergy efficiency is outlined, based on the theoretical minimum exergy demand to drive a process, demonstrating the improvement potentials of a process. The second law efficiency of primary and secondary (recycling) processes has been estimated for nine major non-renewable construction materials: aluminium, steel, copper, cement, concrete, ceramic, glass, polypropylene (PP), and polyvinyl chloride (PVC). These case study materials are selected based on the following criteria: (i) high exergy intensity; (ii) high consumption in the construction sector; and (iii) high exergy use in their manufacturing processes. The selected materials represent nearly 90% (in terms of mass) of the total processed materials used in the construction sector, considering both buildings and civil works (Hoque et al. 2012; Sendra 2008; Smith et al. 2003).

This chapter is organized as follows: the next section presents the methodology adopted in this research; the results and analyses are then introduced in section 3.3; section 3.4 discusses the findings from this analysis; and section 3.5 presents concluding remarks.

3.2 Exergy efficiency

Exergy is lost in all processes as low quality heat or in the form of chemically or physically reactive materials. To estimate the exergy of waste, detailed chemical composition of waste stream is required. Once this is known, an exergy balance of a process can be obtained, as illustrated in equation 3.1:

$$E_{x,\mathrm{in}} = E_{x,\mathrm{prod}} + \Delta E_{x,\mathrm{proc}} + E_{x,\mathrm{waste}} \tag{3.1}$$

where, $\Delta E_{x,\mathrm{proc}}$ is the exergy destruction in the process due to the necessary forces that drive the process; $E_{x,\mathrm{in}}$, and $E_{x,\mathrm{prod}}$ represent the exergy of inputs and useful outputs, respectively; $E_{x,\mathrm{waste}}$ is the exergy of waste including emissions.

The exergy efficiency or second law efficiency (e_2) of a process or a system is the relation between the process products' exergy and the input exergy. It can be calculated as the useful product output divided by the total exergy input of a process as expressed in equation 3.2 (Szargut et al. 1988).

$$e_2 = \frac{E_{x,\,product/s}}{E_{x,\,materials} + E_{x,\,utilities}} \tag{3.2}$$

where, $E_{x,product/s}$ $E_{x,materials}$, and $E_{x,utilities}$ represent the exergy of useful output, input material, and input utilities, respectively. The utilities include water, steam, electricity, and fuels required for the process. Material and utilities required for effluent treatment may also be included in efficiency calculation for proper representation of process exergy efficiency. However, due to limited data on effluent treatment processes in different industrial segments, this study has not considered this process step in exergy efficiency estimation. For any conversion, the theoretical upper limit of e_2 is 100%, which corresponds to the ideal case with no dissipations. The process improvement potentials can be determined by comparing the exergy efficiency of a process in actual industrial practice with the theoretical exergy efficiency. Theoretical exergy efficiency can be calculated as the exergy of useful products ($E_{x,product/s}$) to the theoretical minimum exergy ($E_{x,theoretical\ minimum}$) required to drive the process (equation 3.2). The theoretical minimum exergy for a process is calculated by performing an exergy balance of the exergy inputs and outputs in the theoretical reaction. The theoretical exergy efficiency illustrates the maximum efficiency that can be achieved from a process in an ideal situation.

$$e_2(\text{theoretical}) = \frac{E_{x,\,\text{product}/\,s}}{E_{x,\,\text{theoretical minimum}}} \tag{3.3}$$

Exergy efficiency calculation requires detailed and disaggregated information on material and energy inputs/outputs in each process steps of a production chain, which can be based on the data from theoretical reactions and also from the actual industrial practices. Exergy efficiency of the overall process can be calculated by using equations 3.4 and 3.5 as explained by Ayres and colleagues (1981).

$$e_2(\text{simple chain}) = e_2(1) \cdot e_2(2) \cdot e_2(3) \tag{3.4}$$

$$e_2(\text{branched chain}) = \frac{e_2(3) \cdot \left[e_2(1) \cdot E_{x_1} + e_2(2) \cdot E_{x_2} \right]}{(E_{x_1} + E_{x_2})} \tag{3.5}$$

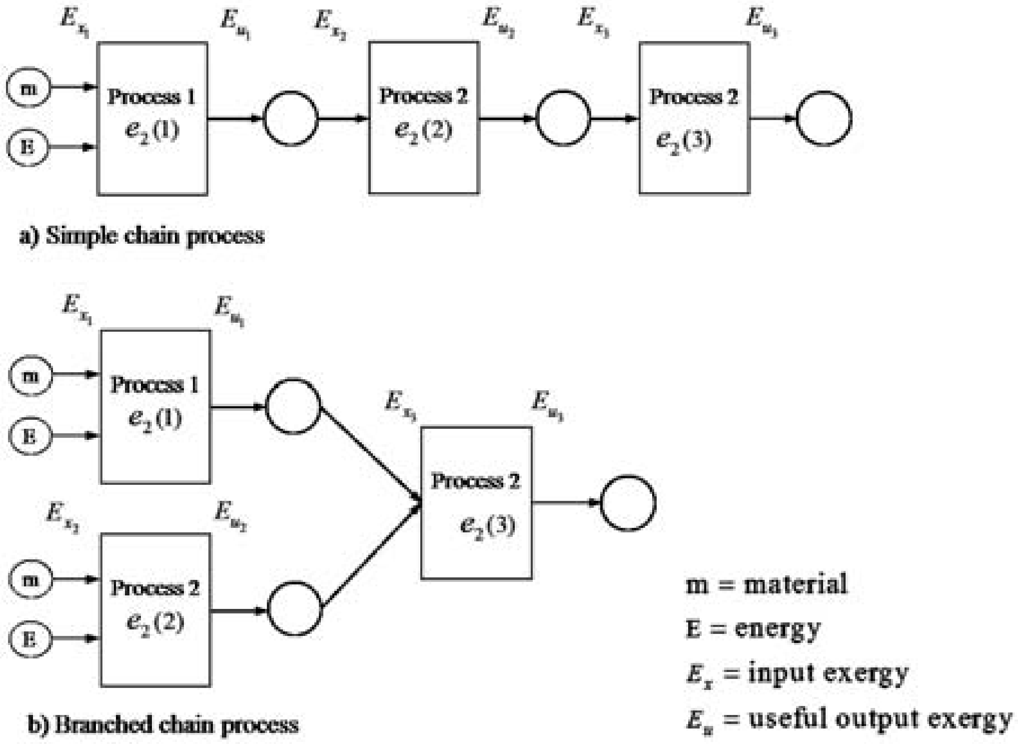


Figure 3.1: Simple and branched chain process efficiency [Adopted from Ayres et al. 1981].

Figure (3.1a) represents a simple chain production process, where the exergy efficiency of the whole production chain is calculated by multiplying the efficiency of unit processes 1, 2, and 3 (euqtion 3.4). Figure (3.1b) represents a branched chain production process and exergy efficiency of the overall process depends not only on the efficiency of unit processes 1, 2, and 3 but also on the inputs to the unit processes 1 and 2 as illustrated in equation 3.5.

3.3 Case studies

The construction sector is one of the largest consumers of steel. It is estimated that global crude steel production in 2010 was 1.4 billion tonnes (Worldsteel 2010) and nearly 50% was used in construction applications. Besides, iron and steel industry is the second-largest industrial user of energy after chemical industry in the European Union 27 (EU-27), which accounts for nearly 17% of industrial energy consumption in 2009 (EEA 2012).

Aluminium is the second most-used metal after steel and is the largest in non-ferrous metal industry in volume of metal produced (Balomenos et al. 2011). In 2010, nearly

26% of the European aluminium end-use went to construction applications (EAA 2010). Aluminium represents 8% of the Earth's crust, being the third most abundant element in the planet followed by oxygen and silicon. At present the only important mineral source is bauxite, which contains 40% to 60% aluminium oxide (Ayres et al. 2006).

Construction is the single largest market of copper (Cu), followed by electronic products, transportation, industrial machinery, and consumer and general products (USGS 2011). Copper consumption in construction applications accounts for 28% of global consumption (LME 2007). Copper scrap recycling contributes significantly to copper supply. Recycled copper met 45.7% of Europes' demand (including Russia) in 2009 (Eurocopper 2009).

Cement and concrete are the major non-metallic mineral processed materials used in construction applications, representing 50% of the total material use in the construction sector (Hoque et al. 2012; Smith et al. 2003). It is estimated that 3.3 billion tonnes of cement and 631.4 billion tonnes of ready mixed concrete were produced globally in 2010 (USGS 2011). Concrete is an established construction material that is widely used in buildings and civil constructions since it is able to withstand moisture and varying weather conditions. It is the second most consumed material in the world after water (Woodward and Duffy 2011).

Flat glass is the second largest sector of the EU-27 glass industry, representing 29% of the total glass production in 2010 (CPIV 2010). European flat glass production was estimated to be 9.4 million tonnes in 2010 (CPIV 2010), out of which nearly 70% were consumed in windows for buildings. The use of ceramic products in construction applications are floor, roof, wall, countertop tiles, sanitary ware, and bricks.

In 2010, European construction sector consumed 9.54 million tonnes of plastics (21% of total European plastics consumption), making it the second largest plastic application after packaging (PlasticEurope 2011). This sector uses them for a wide and growing range of applications including insulation, piping, window frames, and interior design. This growth is mainly due to plastics' unique features, which include: durability and resistance to corrosion, better insulation, cost effectiveness, and minimum operation and maintenance. PVC is the most-used thermoplastic in construction applications. In 2008, world consumption of PVC was estimated to be 34.5 million tonnes and nearly 50% were used in construction applications. Global demand of PP was estimated 36.5 million tonnes in 2009, out of which 5.5% were used in construction applications (GBI research 2010).

Based on the use patterns of the case study materials, as illustrated above, it is obvious that these materials are highly relevant for the construction sector. Additionally, these materials are also important for other sectors in the economy such as automobiles, domestic appliances, electronics, packaging etc. Thus, the outcomes of this study can be useful to assess resource efficiency not only for construction sector but also for other industrial or service sectors.

3.3.1 Steel

Steel industry uses different processes based on the availability and types of material feedstock (especially ores and scrap), fossil fuel, and on the mechanical and chemical properties needed for the final product (Ayres et al. 2006). The integrated primary steel production uses basic oxygen furnace (BOF) process which involves four major steps, namely: palletizing, sintering, pig iron production and finally conversion of pig iron to steel. This study has included coke production as an additional previous step while calculating exergy efficiency of primary steel production. Coke is an important input for steel production as it serves multiple roles including reducing agent, furnace burden support, and fuel.

The exergy efficiency of primary steel production process has been estimated to be 16.3% (table 3.1), assuming a branched chain production process (see figure. B.2 in the appendix B for detailed exergy balance of the steel production process, which has been used for efficiency calculations based on process data). Pelletizing and sintering are responsible for exergy low efficiency of steel production (table 3.1). These are agglomeration process used to meet the specific characteristics required for feed materials, especially in terms of particle size and hardness. Irreversibility associated with the heat transfer and some undesired chemicals, which are formed at higher temperatures such as nitrogen oxide (NO_x) and zinc ferrites ($Zn_xFe_{3-x}O_4$), contributing to greater exergy losses in these process steps (IPPC 2012; De Beer et al. 1998).

Table 3.1: Exergy inputs and outputs in different steps of primary steel production.

Process step	Input exergy (MJ)	Output exergy (MJ)	Exergy efficiency (%)
Coke production	19.21	16.36	85.2
Pellet production	2.70	0.25	9.2
Sintering	0.71	0.08	11.8
Pig iron production	22.43	8.83	39.4
Steel production	12.02	6.76	56.3

Note: Calculation based on the process information available in Alvarado et al. 1999; Ayres and Ayres 1999.

The theoretical minimum exergy demand of the primary steel production process has been estimated assuming the ore as pure ferric oxide (Fe_2O_3) and is reduced to iron (Fe). The theoretical minimum exergy of this process can be estimated from the exergy balance of the following reactions, as illustrated in the following reactions (equations 3.6 and 3.7).

$$6\ C + 3\ O_2 \rightarrow 6\ CO + 823.6\ kJ \tag{3.6}$$

$$2\ Fe_2O_3 + 6\ CO \rightarrow 4\ Fe + 6\ CO_2 + 58.3\ kJ \tag{3.7}$$

$E_{x,theoretical\ minimum} = 676.01$ kJ/kg

Based on this estimation, the theoretical minimum exergy efficiency of steel production has been estimated to be 56.3%.

The exergy efficiency of secondary steel production (steel scrap recycling) has also been studied in this analysis. These analysis bases 100% steel scrap recycling in the electric arc furnace (EAF) to estimate the exergy efficiency of recycling process.) Average energy use in steel scrap recycling has been estimated to be 11.7 MJ/kg (Grimes et al. 2008), representing the exergy efficiency of 35.6% in actual industrial practice. Due to the presence of soil and other impurities, a yield loss of 2.5% has been reported by Fruehan et al. (2000) during steel scrap recycling in the EAF.

The theoretical minimum exergy demand in the secondary steel production process has been estimated based on the exergy required to raise the steel scrap temperature from ambient (25°C) to its melting temperature (1536°C) plus latent heat of fusion, and has been calculated to be 0.96 MJ per kilogram of steel scrap recycled. Based on this estimation, the theoretical exergy efficiency of steel scrap recycling becomes 81.8%.

3.3.2 Aluminum

Primary aluminium production involves two major operations, namely alumina production from bauxite ore (Bayer process) and electrolytic smelting of alumina to pure aluminium (Hall-Héroult process). The Hall-Héroult process account for approximately two-third of the total energy input in primary aluminium production (Balomenos et al., 2011). In addition to the Bayer process and the Hall-Héroult process, this study also considers the production efficiency of caustic soda (NaOH), sulphuric acid (H_2SO_4), hydrogen fluoride (HF), synthetic cryolite (Na_3AlF_6), aluminium fluoride (AlF_3), and carbon anode in order to estimate the exergy efficiency of primary aluminium production. Exergy flows of each of these individual processes have been presented in Table 3.2. Assuming a branched chain production process, exergy efficiency of primary aluminium production has been estimated to be 10.8%.

Table 3.2: Exergy inputs and outputs in different steps of primary aluminum production.

Process step	Input exergy (MJ)	Output exergy (MJ)	Exergy efficiency (%)
NaOH production	1.41	0.18	13.1
H_2SO_4 production	0.96	0.20	20.7
HF production	0.45	0.18	39.1
Bayer process	38.64	3.92	10.1
Synthetic cryolite production	0.65	0.47	73.0
AlF_3 production	0.86	0.76	87.9
Anode baking	19.20	17.42	90.7
Hall-Héroult process	89.29	32.81	36.7

Note: Process inputs and outputs are estimated from Ayres and Ayres 1999; Balomenos et al. 2011.

The Bayer process can be characterized as a low efficient process due to its high fuel consumption for process heating without producing significant increase in the output products' exergy. Besides, a significant portion of the input exergy is embodied in the red mud waste (nearly 43% Fe_2O_3). Red mud can be used as an industrial feedstock rather than an industrial waste. The exergy efficiency of alumina (Al_2O_3) production by the Bayer process has been estimated to be 1.3% taking into account the exergy efficiency of NaOH production. Low efficiency of the Bayer process is mainly because of a cyclic chemical process designed to separate gibbsite ($Al_2O_3 \cdot 3\ H_2O$) from bauxite (equation 3.8), gibbsite calcinations (equation 3.9), and of a series of spontaneous reactions resulting in the production of the red mud waste.

$$Al2O_3 \cdot 3\ H_2O + 2NaOH \rightarrow 2NaAlO_2 + 4H_2O \rightarrow Al_2O_3 \cdot 3\ H_2O + 2NaOH \qquad (3.8)$$

$E_{x,theoretical\ minimum} = 0.007$ MJ/kg

$$Al_2O_3 \cdot 3H_2O + 185.16\ kJ \rightarrow Al_2O_3 + 3H_2O \qquad (3.9)$$

$E_{x,theoretical\ minimum} = 3.818$ MJ/kg

In the Hall-Héroult process, aluminium is produced by the electrolytic reduction of high grade alumina, which is dissolved in a molten bath consisting Na_3AlF_6 and AlF_3 at an approximate 960°C. The Hall-Héroult process shows higher exergy efficiency (42.4%) compared to the Bayer process (10.1%). This increase in exergy efficiency is mainly because of significant increase in products' chemical exergy: alumina (2.0 MJ/kg) is converted to pure aluminium (32.93 MJ/kg) (equation 3.10).

$$2Al_2O_3 + 3C + 2170.9\ kJ \rightarrow 4Al + 3CO_2 \qquad (3.10)$$

$E_{x,theoretical\ minmum} = 21.358$ MJ/kg

The theoretical exergy efficiency of aluminium production has been estimated to be 22.7% using the theoretical minimum exergy required for the chemical changes involved in the production pure aluminium from bauxite ore (equations 3.8-3.10) (see table B.2 in the appendix B for detailed calculation on the theoretical minimum exergy demand of the Hall-Héroult process as an example). The theoretical exergy efficiency of the Bayer process (24.8%) and the Hall-Héroult (91.7%) clearly shows that these processes can be potentially improved; which in turn can improve the efficiency of primary aluminium production process.

Due to the scarcity of bauxite ore and high exergy demand in the primary process, secondary aluminium production (aluminium scrap recycling) has become popular in recent years. Currently more than 90% of the aluminium from construction and demolition waste is being recycled (EAA 2010). In actual industrial practice, the average exergy demand (utility) of scrap recycling is 5.14 MJ/kg (Grimes et al. 2008). From this estimation, the exergy efficiency of secondary aluminium production has been estimated to be 82.6%.

The theoretical minimum exergy demand for aluminium scrap conversion is the exergy required to raise the metal temperature from ambient (25ºC) to its melting temperature (660ºC) plus latent heat of fusion. Based on this assumption, the theoretical minimum exergy demand of aluminium scrap recycling has been estimated to be 0.97 MJ/kg. Thus the theoretical exergy efficiency of secondary aluminium production becomes 92.5%.

3.3.3 Copper

The copper ores typically contain 0.5-1.0% Cu, which makes primary copper production highly exergy intensive. Sulphide ores, the most abundant followed by oxide ores, are crushed and ground and then concentrated to 20-35% Cu. The concentrate is then smelted and converted to 98-99.5% pure blister copper, which produce large quantities of slag and SO_2. Blister copper is further refined to 99.99% plus pure copper cathodes (Alvarado et al. 1999). Oxide ores are broken up and then leached with acid. In an increasing number of plants, the leach solution is first concentrated and purified by solvent extraction before pure copper is recovered by electrowinning.

This analysis includes five major steps namely: sulphide copper ore concentration, roasting and smelting, H_2SO_4 production, sulphide/ oxide copper ore concentration, and electrolytic refining to estimate the exergy efficiency of the primary copper production process. Table 3.3 illustrates the exergy flows of the primary copper production process representing the efficiency of each of these individual process steps, as well as the overall process (1.8%) assuming a branched chain production process.

Table 3.3: Exergy inputs and outputs in different steps of primary copper production.

Process step	Input exergy (MJ)	Output exergy (MJ)	Exergy efficiency (%)
Sulfide Cu-ore concentration	172.13	26.68	15.5
Roasting and smelting	49.75	11.52	23.2
H_2SO_4 production	11.50	5.07	44.1
Sulfide/Oxide Cu-ore concentration	42.17	0.58	1.4
Electrolytic refining	2.95	2.11	71.5

Note: Process inputs and outputs are estimated from Alvarado et al. 1999; Ayres and Ayres 1999.

Theoretical minimum exergy required to produce copper from sulphide ore (considering pure chalcopyrite) has been estimated to be 0.66 MJ/kg of copper, calculated from the following reactions (equations 3.11 and 3.12). Based on this estimation, the theoretical exergy efficiency of primary copper production has been quantified 50.9%.

$$CuFeS_2 + {}^3/_2O_2 \rightarrow FeO + CuS + SO_2 + 222.6\ kJ \qquad (3.11)$$

$$CuS + O_2 \rightarrow Cu + SO_2 + 243.7\ kJ \qquad (3.12)$$

$E_{x,theoretical\ minimum} = 0.66$ MJ/kg

Secondary copper can be produced from copper scrap and other copper containing materials by pyro metallurgical and hydrometallurgical processes that are similar to those used in primary metal production. Secondary process uses 6.3 MJ of exergy (utility) with an average yield of 91% (Ruhrberg 2006). With this estimation, the exergy efficiency of the secondary process has been estimated to be 22.9%.

The theoretical exergy efficiency of secondary copper production has been quantified 70.7%. This estimation is based on the theoretical minimum exergy demand of 0.61 MJ per kg of copper scrap recycled, assuming the exergy required raise the scrap temperature from ambient (25ºC) to its melting temperature 1090ºC plus latent heat of fusion.

3.3.4 Cement

The choice of Portland cement production process is primarily motivated by the nature and availability of fuel and raw materials. Clinker is an intermediate product in the cement production process in which the Portland cement is a blend of finely ground clinker, additional mineral components, and gypsum. Clinker production in the rotary kiln is the most energy intensive step of cement production. Dry process is preferred due to reduced energy demand compared to wet process. Nearly 90% of Europe's cement production is from dry process kilns (IPPC 2010). This study estimates the exergy efficiency of CEM I Portland cement assuming a mixture of 95% clinker and 5% gypsum. In the clinker production process, limestone and oxides of calcium, silicon, aluminium, and iron are crushed and milled into a raw meal. The heating of the raw meal in the kiln system activates the dissociation of calcium carbonate to free calcium oxide, which then forms hydraulic compounds with the other oxides. Clinker burning is considered to be one of the most complicated thermal processes, since this is accompanied by a large number of chemical and structural transformations. Besides, the quality of the resulting product is significantly influenced by the type of raw material and the burning method. Cement production process involves raw feed preparation, clinker production, and cement blending process steps. Assuming a simple chain process, the exergy efficiency cement production has been estimated to be 12.6% (table 3.4).

Table 3.4: Exergy flows in different steps for the production of 1 kg of cement.

Process step	Input exergy (GJ)	Output exergy (GJ)	Exergy efficiency (%)
Raw feed preparation	0.49	0.28	57.2
Clinker production	3.20	0.93	29.0
Cement blending	1.22	0.93	75.9

Note: Estimation based on the Catalan (Spain) cement industry data and process information available in Huntzinger and Eatmon 2009; Kolip and Savas 2010; IPPC 2010; Taylor 1997.

The chemical changes occur during clinker burning is presented in 3.5, which also present the theoretical minimum exergy required to produce clinker. The theoretical exergy efficiency of cement production has been estimated to be 34.1%, taking into account the theoretical minimum exergy demand in raw feed preparation (0.009 MJ/kg), clinker production (2.18 MJ/kg), and cement blending (0.003 MJ/kg).

Table 3.5: Clinker formation reactions in a rotary kiln (Taylor 1997).

Reaction	ΔH (kJ/mol)	ΔH (kJ/kg)^A	Inputs (kg)^B	Outputs (kg)^C	ΔH_{tot} (A×B; A×C) (kJ)
$CaC0_3 \rightarrow CaO + CO_2$	178.36	1782	1.41		2512.62
$4SiO_2 \cdot Al_2O_3 \cdot H_2O \rightarrow \alpha\text{-}Al_2O_3 + 4SiO_2 + H_2O$	80.71	224	0.034		7.62
$2SiO_2 \cdot Al_2O_3 \cdot 2H_2O \rightarrow \alpha\text{-}Al_2O_3 + 2SiO_2 + 2H_2O$	138.89	538	0.139		74.78
$2FeO \cdot OH \rightarrow \alpha\text{-}Fe_2O_3 + H_2O$	45.15	254	0.015		3.81
$2CaO + SiO_2 \rightarrow \beta\text{-}C_2S$	-126.42	-734		0.126	-92.48
$3CaO + SiO_2 \rightarrow C_3S$	-113.02	-495		0.639	-316.31
$3CaO + \alpha\text{-}Al_2O_3 \rightarrow C_3A$	-7.3	-27		0.112	-3.024
$4CaO + \alpha\text{-}Al_2O_3 + \alpha\text{-}Fe_2O_3 \rightarrow C_4AF$	-51.03	-105		0.012	-1.26
$6CaO + 2\ \alpha\text{-}Al_2O_3 + \alpha\text{-}Fe_2O_3 \rightarrow C_6A_2F$	-109.91	-157		0.061	-9.58
		Total	1.598	0.95	2176.2

The low exergy efficiency of cement production is associated with exergy losses due to irreversibility in raw feed preheating and clinker cooling (Koroneos et al. 2005). Efficiency improvement in the cement sector mainly depends on the efficiency of clinker production. The new cement plants recover exhaust heat from the kiln, utilizing to preheater and/or calciner, and thus further optimisation of these plants is difficult to achieve. This study calculates the exergy efficiency of 29.0% for clinker production in actual industrial practices, whereas the theoretical limit is 37.7%. Hence, the two main ways of increasing efficiency of cement production can be the use of alternative material and fuel. The former involves the use of reduced amount of clinker in the finished cement, known as clinker factor reduction or material substitution. There are two main alternatives to clinker in cement: blast furnace slag and pulverized fuel ash or fly ash. Alternative fuels include organic waste, animal feed, and biomass.

3.3.5 Concrete

Concrete is a mixture of aggregates (usually sand, gravel and crushed stone) and paste (comprised of cement and water) that forms a rocklike mass as the paste hardens because of the chemical reaction of cement and water. Concrete is widely recognized as one of the most sustainable building materials when both energy consumption during its production and inherent properties are taken into account. However cement, the main ingredient of concrete, contains significant embodied exergy and cement manufacturing is also recognized as an exergy intensive process as well as a major source of carbon dioxide (CO_2). Exergy inputs and outputs to produce 1 kg of concrete are illustrated in table 3.6, where cement production efficiency has been taken into account to estimate the exergy efficiency of overall concrete production process. Assuming a simple chain production process, the exergy efficiency of concrete production is accounted for 9.5%.

Table 3.6: Exergy inputs and outputs for the production of 1 kg concrete.

Material/ utility	Input exergy (MJ)	Output exergy (MJ)	Exergy efficiency (%)
Cement	0.15		12.6
Crushed stone, sand and gravel	0.09		
Utility	0.04		
Concrete		0.21	75.2

Note: Process data adopted from Ecoinvent 2009.

Theoretical minimum exergy demand in concrete production is the exergy required to mix the ingredients, which is estimated to be 0.027 MJ/kg. With this estimation, theoretical exergy efficiency of concrete production becomes 26.9%.

Concrete recycling has gained significant importance since it protects natural resources and eliminates the need for disposal by using the readily available concrete as an aggregate source for new concrete or other applications such as road construction (Woodward and Duffy 2011). This study estimates the exergy efficiency of concrete recycling assuming the output product as aggregate. The theoretical and practical exergy efficiency of concrete recycling has been estimated to be 67.8% and 75.9%, respectively. Regulatory constrains have facilitated the recycling or reuse of waste concrete in recent years. Recycled concrete can be used as aggregate in new concrete, particularly the coarse portion. When using the recycled concrete as aggregate, the following issues should be taken into consideration: (i) recycled concrete as aggregate will typically have higher absorption and lower specific gravity than natural aggregate; (ii) the chloride content of recycled aggregates is of concern if the material will be used in reinforced concrete. This is particularly an issue if the recycled concrete is from pavements in northern climates where road salt is freely spread in the winter. The alkali content and type of aggregate in the system is probably unknown, and therefore if mixed with unsuitable materials, a risk of alkali-silica reaction is possible.

3.3.6 Ceramic

Ceramic products are manufactured from clays, non-metallic inorganic materials, and metallic oxides. The raw materials are heat-treated after adjustment of the grain size and moisture, and some of them are completely molten to be formed into ceramics; while others are formed, heat-treated, and made into the ceramic products in the sintered state immediately before being molten. Firing of ceramic bodies at high temperature usually transforms the constituent minerals into a mixture of new minerals or glassy phase. The energy mix in the European ceramic industry is typically 80% natural gas and 20% electricity (IPPC 2007). In the development of ceramic properties during firing of ceramic body, the most important change involves the breakdown of lattice structure of the clay minerals to form new crystalline structure or glassy phase. The firing temperature varies according to the mineralogy of clay: usually commences at about 900°C and is completed by about 1300°C. This study estimates the exergy efficiency of ceramic tile production taking into account the raw feed preparation, extrusion and drying, and firing and cooling process steps. Table 3.7 illustrates the exergy flows in the production of 1 kg ceramic tile, showing very low exergy efficiency (4.6%) in present industrial practice.

Table 3.7: Exergy inputs and outputs for the production of 1 kg ceramic tile.

Process step	Input exergy (MJ)	Output exergy (MJ)	Exergy efficiency (%)
Raw feed preparation	0.14	0.11	75.2
Extrusion and drying	1.60	0.83	51.9
Firing and cooling	6.63	0.79	11.9

Note: Estimation based on the process information available in Agrafiotis and Tsoutsos 2001; Ecoinvent 2009; IPPC 2007.

To calculate the theoretical exergy efficiency, it is assumed that carbonate minerals are calcined at high temperature to form metal oxides as illustrated in the following reactions (equations 3.13 and 3.14).

$$CaCO_3 \cdot MgCO_3 + 304.4\ kJ \rightarrow CaO + MgO + 2CO_2 \quad (3.13)$$

$$CaCO_3 + 178.36\ kJ \rightarrow CaO + CO_2 \quad (3.14)$$

The theoretical minimum exergy demand of ceramic tile production is quantified 1.69 MJ/kg, taking into account the heat of formation and thermal energy required to raise the temperature 25 to 1300ºC. Based on this estimation, the theoretical exergy efficiency of ceramic tile production has been quantified 39.4%.

At present, mainly primary ceramic wastes (generated during the production process) are recycled, whereas most of the secondary ceramic wastes are sent to the land fill site. This study calculates the exergy efficiency for ceramic recycling assuming the output product as aggregate. The theoretical and practical exergy efficiency of ceramic tile recycling has been estimated to be 25.0% and 26.1%, respectively; assuming no material loss while crushing process.

In the ceramic industry, appreciable amounts of energy could be saved or conserved by preventing of leakage in the kilns and controlling of combustion, modifying the process design and/or equipment to recover heat from the kiln in the process of ceramic-firing.

The substitution of natural aggregates with ceramic and porcelain wastes produces a significant increase in compression resistance, making them suitable for the manufacture of concrete with various resistance categories (Valdés et al. 2010).

3.3.7 Glass

Glass making is an energy intensive process, and the energy delivered to glass melting furnace is either by the combustion of fossil fuels or by electrical heating or by a combination of both techniques. The conventional and most commonly used method to provide heat in the glass melting furnace is by burning fossil fuels above the batch. The temperature necessary to melt and to refine the glass ranges between 1300 and 1550ºC (IPPC 2010a). The first reactions (decarbonisation) occur at around 500ºC and the raw materials begin to melt at between 750 and 1200ºC. The silica from the sand combines with the sodium oxide from the soda ash and with other batch materials to form silicates. At the same time, large amounts of gases escape through the decomposition of the hydrates, carbonates, nitrates and sulphates; giving off water, carbon dioxide, oxides of nitrogen, and oxides of sulphur. In general, the glass melting accounts for more than 75% of the total energy demand of glass production.

The large inefficiency in the glass production process is mainly because of the exergy destruction in fuel combustion and heat transfer process. It is estimated that up to 30% of the heat from melting is expelled through the exhaust gases (Sinton 2004). Furnaces equipped with regenerator or recuperator can recover some of this heat, which can potentially be used to preheat the batch or cullet. Preheating of the feed materials up to 400ºC may reduce 16% of energy use in the glass melting process (Plum et al. 2002). Exergy flows in the production of 1 kg of flat glass are illustrated in table 3.8, showing an exergy efficiency of 11.5% in actual industrial practices.

Table 3.8: Exergy inputs and outputs for the production of 1 kg flat glass.

Material/ Utility	Input exergy (MJ)	Output exergy (MJ)	Exergy efficiency (%)
Raw material	0.24		
Utility	8.270		
Flat glass		0.98	11.5

Note: Process inputs and outputs estimated based on the data available in IPPC 2010

The theoretical minimum exergy demand of glass melting process has been estimated based on the heat of reaction for glass formation plus thermal energy required to raise the temperature to 1550ºC, which is 2.38 MJ/kg. With this quantification, the theoretical exergy efficiency of glass production has been estimated to be 36.7%. It is assumed that the carbonate raw materials are calcined at high temperature to form metallic oxides (equations 4.14 and 3.15).

$$Na_2CO_3 + 323\ kJ \rightarrow Na_2O + CO_2 \qquad (3.15)$$

One of the most important properties of glass is that it can, in theory, be recycled an indefinite amount of times without any quality degradation. Use of recycled glass (commonly referred to as cullet) with the glass batch can significantly reduce the process exergy demand since chemical exergy required for glass formation has already been provided. As a general rule, every 10 % increase in cullet usage results in an energy savings of 2-3 % in the melting process (IPPC 2010a). At present, flat glass production uses nearly 10-40% cullet with the virgin raw materials based on the quality requirements. This study estimates the exergy efficiency of flat glass recycling assuming 30% cullet is recycled with virgin raw materials, given the fact that excess cullet use may produce low quality finished product. With this estimation, the theoretical and industrial exergy efficiency of secondary glass production have been estimated to be 35.7% and 14.2%, respectively.

3.3.8 Polypropylene

PP is polymerized from propylene, which is extracted by cracking naphtha or gas oil in a steam-cracker. Ethylene and propylene are co-produced in the naphtha cracking process. PP is produced in a low-pressure process. Different polymerization processes are used in the production of PP such as solution polymerization, bulk polymerization in liquid propylene, and several gas-phase processes. Exergy inputs and outputs in different steps of the production chain to produce 1 kg PP is illustrated in table 3.9. Assuming a branched chain production process, this analysis estimates the exergy efficiency of 54.6% for PP production process.

Table 3.9: Exergy inputs and outputs of PP resin production.

Process step	Input exergy (MJ)	Output exergy (MJ)	Exergy efficiency (%)
Naphtha production	81.16	61.40	75.7
Ethylene production	5.71	3.98	69.7
Propylene production	56.68	45.19	79.7
Propylene polymerization	50.60	46.31	91.5

Note: Process inputs and outputs estimated based on the process flow information available in Ayres and Ayres 1999; Narita et al. 2002.

Naphtha can vary in composition and boiling range depending on source and refinery conditions. Typical yields from naphtha steam cracking in Europe and Asia Pacific are ethylene (29-34%), propylene (13-16%), butadiene (4-5%), Aromatics (10-16%), methane (13-14%), hydrogen (1%), and other minor hydrocarbons. A series of chemical reactions involved in naphtha cracking process and can be simplified as the following reactions (equations 3.16 and 3.17). Thermodynamic theoretical minimum energy requirement is estimated to be 5.0 MJ/kg taking into account the thermochemical data of the chemical reactions involved in the production process (Ren et al. 2006). Based on this estimation, the theoretical exergy efficiency of PP production is accounted for 60.8%.

$$C_xH_y \rightarrow CH4 + C_2H_4 + C_2H_6 + C_3H_6 + C_4H_6 + C_4H_8 + C_6H_6 + C_6H_5CH_3 + n\text{-}C_uH_v \quad (3.16)$$

$$C_3H_8 + 129.4\ \text{kJ} \rightarrow C_3H_6 + H_2 \quad (3.17)$$

The major problem of recycling plastic waste is greater inhomogeneity of the polymers present in the waste. However, due to environmental problem plastic waste disposal and incineration are prohibited to many nations of the EU. As a result, various energy and material recovery methods to recycle plastic waste are becoming more popular in recent years. This analysis estimates the theoretical and practical exergy efficiency of the secondary PP production process assuming an average yield of 90% PP from the secondary material. Based on this assumption, the industrial and theoretical exergy efficiency of PP recycling has been accounted for 70.4% and 90.3%, respectively.

3.3.9 Polyvinyl chloride

The PVC production is considered as a complex industrial process since multiple reactions are involved in the production chain such as naphtha to ethylene, ethylene to ethylene dichloride (EDC), EDC to vinyl chloride monomer (VCM), and PVC from VCM polymerization. This study assumes that hydrochloric acid (HC1) generated by the thermal decomposition of EDC is used as the raw material for the oxy-chlorination process. Therefore, the exergy efficiency estimation includes HCl as a useful by-product. Polyvinyl chloride is commercially produced by bulk, suspension emulsion, and solution polymerization. The suspension process is the major manufacturing technique, nearly 80% of the total PVC is produced by suspension polymerization. Exergy flows of the PVC production process to produce 1 kg PVC resin has been is illustrated in table 3.10, from which the exergy efficiency of PVC production is accounted for 23.7% in present industrial practice.

Table 3.10: Exergy inputs and outputs of PVC resin production.

Process step	Input exergy (MJ)	Output exergy (MJ)	Exergy efficiency (%)
Naphtha production	37.15	28.09	75.6
Ethylene production	32.81	22.90	69.8
Ammonia (NH_3) production	0.24	0.16	67.0
Chlorine (Cl_2) production	5.33	2.30	43.1
VCM production	36.74	21.99	59.8
Vinyl chloride polymerization	24.38	19.66	80.6

Note: Calculation based on the process flow information available in Ayres and Ayres 1999; Narita et al. 2002; Ren et al. 2006.

To calculate the theoretical minimum exergy required for PVC production, the following reactions (equations 3.18-3.21) have been considered where ethylene is converted to PVC through formation of EDC and VCM (Weissermel and Arpe 19997). The theoretical exergy efficiency is estimated to be 52.3% analysing the thermochemical data of the chemical reactions involved in the PVC production process.

$$CH_2{=}CH_2 + Cl_2 \rightarrow CH_2Cl\text{-}CH_2Cl + 209.1\text{ kJ} \quad (3.18)$$

$$CH_2Cl\text{-}CH_2Cl + 192.7\text{ kJ} \rightarrow CH_2{=}CHCl + HCl \quad (3.19)$$

$$2CH_2{=}CH_2 + Cl_2 + HCl + {}^{1}/_{2}O_2 \rightarrow 2\ CH_2Cl\text{-}CH_2Cl + H_2O + 510.3\text{ kJ} \quad (3.20)$$

In the suspension polymerization process VCM is fed to a reactor in doses, together with a suspension stabilizer, a pH buffer, an anti-foam agent and an initiator (e.g. organic peroxides). VCM reacts to form PVC as follows with up to 80-85% yield:

$$nCH_2{=}CHCl \rightarrow CH_2 - CHCl - CH_2 - CHCl - \qquad (3.21)$$

Due to the presence of high chlorine content, some of the recycling techniques are not favourable for PVC. In particular, landfilling and composting are not suitable because of known and unknown hazards associated with the oxidative degradation of PVC in the environment (Sadat-Shojai and Bakhshandeh 2011). Incineration and pyrolysis may also be disfavoured because of the large amounts of hydrogen chloride and other toxic products are produced.

Thus, mechanical and chemical recycling are the two main processes of PVC recycling. The former is preferred when the source of PVC waste is known. This analysis estimates the exergy efficiency of mechanical recycling of PVC assuming an average yield of 90% PVC from the secondary material. Based on this estimation, theoretical and industrial exergy efficiency of PVC recycling has been quantified 90.5% and 54.2%, respectively.

3.4 Discussion

This section is not intended to make specific proposals for improving the manufacturing system but to determine how efficiently today's systems perform and to pinpoint the improvement potentials of the analysed processes. Table 1 presents the exergy efficiency of the case study materials in present industrial practices both for primary and secondary production processes, demonstrating the corresponding theoretical exergy efficiency. This table clearly represents that exergy resources are being used very inefficiently, and there is a wide margin to improve the current technologies. Ideally, the exergy efficiency of the case study materials can be improved from 1.1% (ceramic tile recycling) up to 49.1% (primary copper production). Among the primary processes analysed in this study, PP production has been found to be the most efficient process with an exergy efficiency of 53.4%, followed by PVC (23.7%) and steel (16.3%).

Table 3.11: Exergy efficiency of construction materials: primary and secondary manufacturing processes.

Material	Primary production process			Secondary production process		
	Exergy efficiency, e_2 (%)		Improvement potential (%)	Exergy efficiency, e_2 (%)		Improvement potential (%)
	Industrial practice	Theoretical		Industrial practice	Theoretical	
Steel	16.3	56.3	40.0	35.6	81.8	46.2
Aluminium	10.8	22.7	11.9	82.6	92.5	9.6
Copper	1.8	50.9	49.1	22.9	70.7	47.8
Cement	12.6	34.1	21.5	-	-	-
Concrete	9.5	26.9	17.4	67.8	75.9	8.1
Ceramic tile	4.6	39.4	34.8	25.0	26.1	1.1
Glass	11.5	36.7	25.2	14.2	35.7	21.5
PVC	23.7	51.0	27.3	54.2	90.5	36.3
PP	53.4	60.8	7.4	70.4	90.3	19.9

The analysis also shows that the secondary production process (recycling) has a great potential to achieve more efficient industrial sector since exergy loss in secondary process is far lower compared to primary process (Table 2). It is widely acknowledged that the energy intensity of most of the industrial processes is at least 50% higher than the theoretical minimum determined by the basic laws of thermodynamics (IEA, 2006). However, results of this analysis show that the actual energy intensity is much higher when exergy based analysis is performed. Table 2 illustrates the practical exergy inputs and theoretical exergy demand in present technologies of the case study materials. These figures demonstrate that primary metal production contributes greater exergy losses.

Table 3.12: Exergy inputs in primary and secondary production process for 1 kg product output based on present industrial practice and theoretical minimum requirements.

Material	Exergy input in the primary production process (MJ)			Exergy input in the secondary production process (MJ)		
	Industrial practice	Theoretical demand	Difference (industrial-theoretical)	Industrial practice	Theoretical demand	Difference (industrial-theoretical)
Steel	31.54	11.90	19.64	19.00	8.26	10.74
Aluminium	129.75	43.85	85.90	39.87	35.62	4.25
Copper	236.22	6.89	229.33	8.40	2.72	5.68
Flat glass	8.54	2.66	5.88	6.85	2.73	4.12
Ceramic tile	7.44	1.84	5.60	0.78	0.75	0.03
Concrete	0.74	0.53	0.21	0.22	0.19	0.03
PP	85.14	76.53	8.61	65.82	51.30	14.52
PVC	115.91	87.89	28.02	36.27	21.73	14.54
Cement	3.70	2.52	1.18	-	-	-

The results of this study suggest that radical changes are needed in overall processes of the case study materials in order to achieve major breakthroughs in the exergy efficiency of the industry. Changes in process design and development of achievable technology is required in order to improve the resource sustainability of current industrial sector. An example of the achievable technologies that could produce such changes is described briefly in the following section for aluminum production.

The Boehmite process uses similar process flow like the Bayer process but replaces gibbsite seeding with boehmite seeding, and an optimization can be achieved through precipitation of monohydrate (boehmite) rather than trihydrate (gibbsite) alumina under atmospheric pressure in temperatures lower than 90°C (Dash et al., 2009; Panias et al., 2003). Thus, the Boehmite process can be expressed as equation (3.21)

$$Al_2O_3 \cdot 3H_2O + 2NaOH \rightarrow 2NaAlO_2 + 4H_2O \rightarrow Al_2O_3 \cdot H_2O + 2NaOH + 2H_2O \qquad (3.21)$$

The process is no longer a chemical cycle like the Bayer process, the final product boehmite differs from the initial gibbsite, producing a product with higher exergy value (chemical exergy of boehmite and gibbsite is 1.60 and 0.18 MJ/kg respectively). Calcination of boehmite to alumina requires 126.46 kJ less energy compared to gibbsite calcinations, equations (3.7) and (3.22).

$$Al_2O_3{\cdot}H_2O + 58.7\ kJ \rightarrow Al_2O_3 + 3H_2O \qquad (3.22)$$

The entire alumina production process utilizing the Boehmite process, when compared to the conventional Bayer process, can achieve 19% energy savings and 2% increase in the exergy efficiency (Balomenos et al., 2011). Process efficiency can also be improved by utilizing the high exergy embodied red mud waste instead of sending to landfill. The relatively high exergy embodied in the red mud is mainly due to its high content of Fe_2O_3, which could characterize red mud as an industrial feedstock rather than an industrial waste.

High temperature Carbothermic reduction is a direct chemical reduction of alumina to aluminium, an alternative to the electrolytic reduction. This process can be theoretically described by the following chemical reaction occurring at temperatures higher than 1900°C:

$$Al_2O_3 + 3C + 672.1kJ \rightarrow 2Al + 3CO \qquad (3.22)$$

The main exergetic benefit from replacing the electrolytic reduction of alumina with a Carbothermic process is that carbon will be used as a direct reducing agent supplying the 47% of the total energy for the process instead of the 8% that is currently being utilized as consumable carbon anodes (Balomenos et al., 2011). The high exergetic cost of transforming carbon into electricity to drive the redox reaction will be avoided, while the alumina reduction will take place in a three-dimensional space thus avoiding heat losses due the volumetric inefficiency of the Hall-Héroult process.

3.4.1 Data quality and uncertainty

The accuracy of process efficiency analysis depends on the quality of the data, which due to industry confidentiality is not always available. The data used in this case study comes from different sources and vary in uncertainty and quality. The data for the calculations comes from: (i) theoretical calculations, (ii) process data from industry (Best Available Techniques (BAT) reference documents from Joint Research Centre (JRC) of the European Commission, published literature, technical reports, and other technologies), and (iii) confidential information. This analysis acquired data based on the degree of disaggregation so that process improvements can be calculated at unit process level.

Given the wide variation in published figures and difficulty in establishing a single global factor, a sensitivity analysis is performed to identify the robustness of input data. The range of uncertainty is calculated given the quality of the data for each of the materials of the analysis. For example, literature data show that the process exergy demand range of 120-218.44 MJ/kg and 5.14-10.92 MJ/kg for primary and secondary aluminium production, respectively (Ayres and Ayres, 1999; Balomenos et al., 2011; Choate and Green, 2003). Such a broad range is due to the varying scopes of the studies, including differences in defining system boundary, technology assumptions, and region-specific production processes based on the availability of raw materials and energy sources (see Table (B.4) in the appendix A for process exergy input ranges of the case study materials). These input values account for the exergy efficiency of 6.3-11.4% and 71.4-82.6% for primary and secondary aluminium production processes respectively (see Tables (B.5) and (B.6) in the appendix B for detailed calculations).

3.5 Conclusion

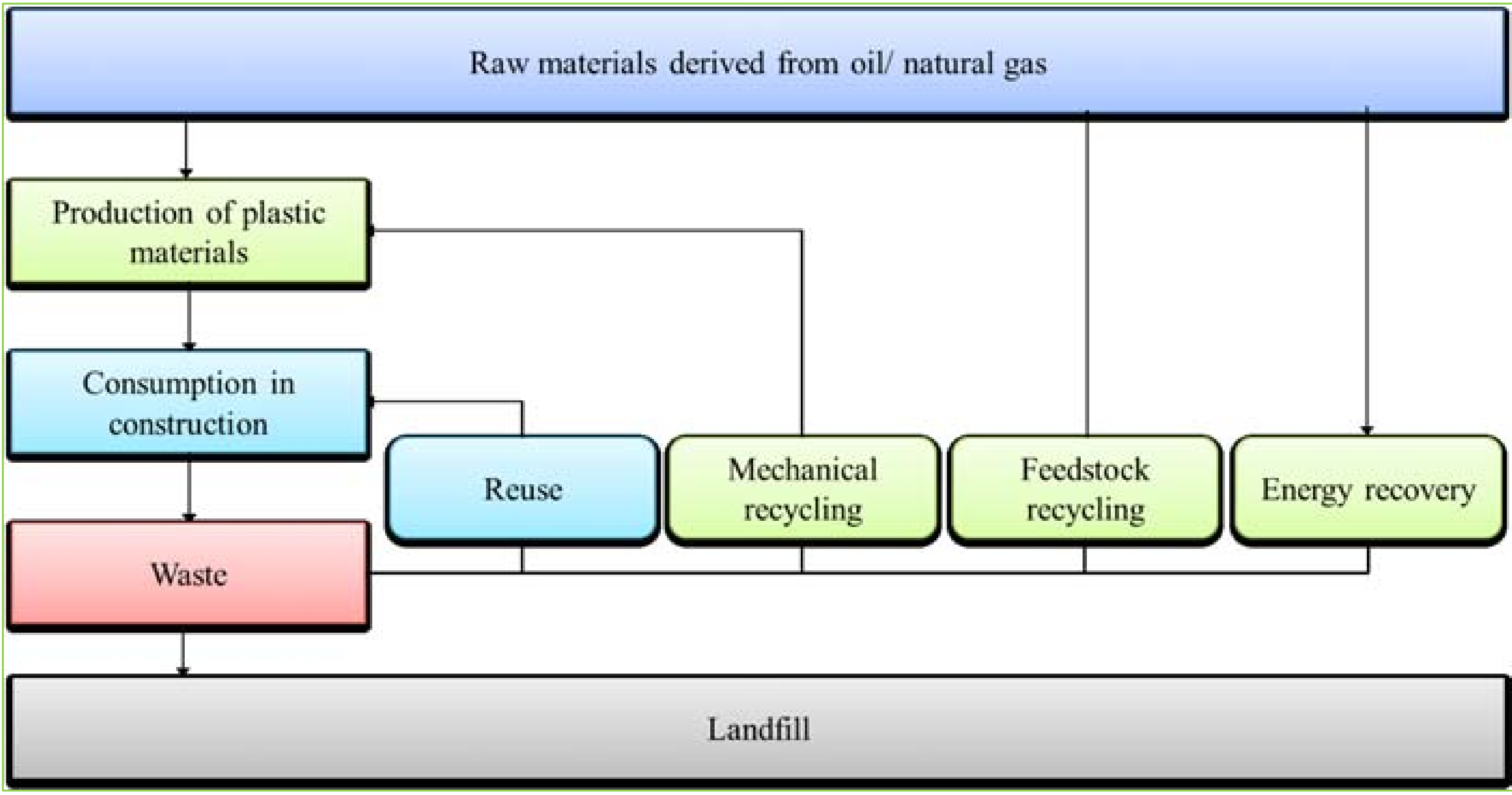
In this study, exergy efficiency of nine major non-renewable construction material manufacturing has been analyzed for both primary and secondary production processes, namely: aluminum, copper, steel, cement, concrete, ceramic, glass, PP, and PVC. The results obtained from this analysis suggest that a potential improvement is required in existing processes, since these processes can operate using significantly less exergy inputs in primary production, from 0.03 MJ/kg (recycling of concrete and ceramic) up to 229.33 MJ/kg (copper). It appears from the results that secondary production (recycling) has great potentials to achive a more efficient industrial sector.

This study clearly demonstrates that exergy resources are used very inefficiently in present industrial practices, and technically there is a wide margin to improve the case study processes. This study shows the potentials of using exergetic efficiency analysis through possible quantificantions of exergy losses in unit operations of the case study materials.

Supporting Information (Appendix B): This supporting information provides descriptions of chemical exergy calculations, calculations of theoretical minimum exergy demand in case study processes, and additional information about the data used in the case study analysis.

CHAPTER 4

Exergetic life cycle assessment



Plastic life cycle

Hoque, M. R., X. Gabarrell Durany, G. Villalba Méndez, and C. Sendra Sala. 2013. Exergetic life cycle assessment: An improved option to analyze resource use efficiency of the construction sector. In: *Sustainability in Energy and Building: Smart Innovation, Systems and Technologies*, Hakansson et al. ed., 22:313-321. Berlin, Heidelberg: Springer Berlin Heidelberg.

This study presents an effort to pinpoint how efficiently resources are used in the construction sector applying exergetic life cycle assessment methodology in a cradle-to-grave life cycle approach. Polypropylene (PP) and polyvinyl chloride (PVC), two widely used thermoplastics in construction applications, are chosen as case study materials in this analysis involving raw material extraction, resin manufacturing, and post-consumer waste management life-cycle stages. Overall life cycle exergy efficiency of PP and PVC has been quantified 27.1% and 9.3%, respectively, characterized by a low efficiency of manufacturing and recycling processes for both materials. Efficiency improvement of manufacturing and recycling processes will thus reduce exergy losses from the system. From resource conservation point of view, mechanical recycling can be the viable option for end-of-life plastic waste management, since it loops materials back directly into new life cycle, providing reduced primary resource inputs in the production chain and associated environmental impacts.

4.1 Introduction

More recently, increasing awareness about the impacts associated with resource use, as well as their scarcity, has led to efforts to reduce energy dependency and to shift industrial activities towards improved technologies. One of the major efforts in achieving this goal is to increase the efficiency of present industrial processes. Adequate evaluation of resource consumptions and environmental impacts throughout the products' life cycle is critical for the proper evaluation of technologies. Life cycle assessment (LCA) is one of the most popular tools to compare different scenarios of products' end-of-life. An LCA consists of three main steps: determination of mass and energy in- and out flows through all stages of the life cycle; evaluation of the environmental impacts associated with resource consumption; and ways to decrease the environmental, economic and social burdens (Dincer and Rosen 2007).

Apart from LCA, a more recent approach in order to assess the sustainability of technological options is the thermodynamic or exergetic life-cycle assessment (ELCA). The ELCA examines exergy flows and seeks to reduce exergy destructions and to improve the efficiency of processes (Cornelissen 1997). Conventional energy efficiency (refers to first law analysis) only identifies losses of work; however, the exergy analysis (known as second law analysis) takes the entropy production into consideration by including irreversibilities (Dincer and Rosen 2007). Therefore, exergy analysis offers useful insights into process analysis. The thermodynamic analysis of life cycle shows a cumulative loss of exergy due to entropy generation. Resource extraction from the ecosphere, conversion of the resources into products and wastes, and irreversibility can be analyzed in exergy terms, showing the role of process efficiency in sustainability. The ELCA uses the same framework as the LCA, but the additional criterion is the life-cycle irreversibility, the loss of exergy during the complete life cycle (Cornelissen 1997). Thus, life cycle irreversibility can be used as the measure of inefficient use of natural resources. The ELCA has been applied to account the depletion of natural resources (Dincer and Rosen 2007), exergy input to production system (Talens Peiró et al. 2010), resource consumption in the built environment (De Meester et al. 2009); however, it can also be a useful tool to assess the inefficiency of a system since it shows in which component the losses of natural resources take place (Dincer 2002). With this information better proposals for reducing the loss of natural resources can be obtained.

Consequently, exergy-based analysis can be used as a powerful tool for process optimization.

Construction sector is the second largest consumer of plastics after packaging sector. European construction sector consumed 9.5 million tonnes of plastics in 2010, representing 21% of the total plastic consumption in Europe (PlasticsEurope 2010). The construction industry uses them for a wide and growing range of applications including insulation, piping, window frames, and interior design. This growth is mainly due to plastics' unique features, which include durability and resistance to corrosion, better insulation property, cost efficiency, minimum operation and maintenance, hygienic, and sustainability (PlasticsEurope 2010). Despite recent advances on closed loop industrial ecology concept, 49% of all the plastic wastes generated in Europe are still disposed of to landfill (EuPR 2010), a management alternative that generates severe environmental problems due to their low density, resistance to biological degradation, and combustible nature. Consequently, extraction of finite natural resources is increasing to meet the excess demand of primary material manufacturing. From energy conservation point of view, disposal of plastic waste to landfill also mean substantial exergy losses as these materials contain significant embodied exergy. Therefore, plastic waste recycling provides opportunities of reduced oil usage, carbon dioxide emissions and the quantities of waste requiring disposal (Hopewell et al. 2009). Reuse and recycling of plastic waste will therefore have a major implication on both efficient resource use and reduced environmental impacts. In recent years, plastic recycling has become more popular in the European Union (EU) due to regulatory limitations. Overall recovery of building and construction plastic waste increased 4.3% in 2010 compared to 2009, includes the recovery of 44.7% PVC and 5.1% PP waste. Figure 4.1 shows the building and plastic wastes recovery in European countries in 2010, showing that the recycling of plastic waste, generated from building and construction sector, is still very low compared to energy recovery and landfill. It is also noticed that feedstock recycling within the European countries is negligible.

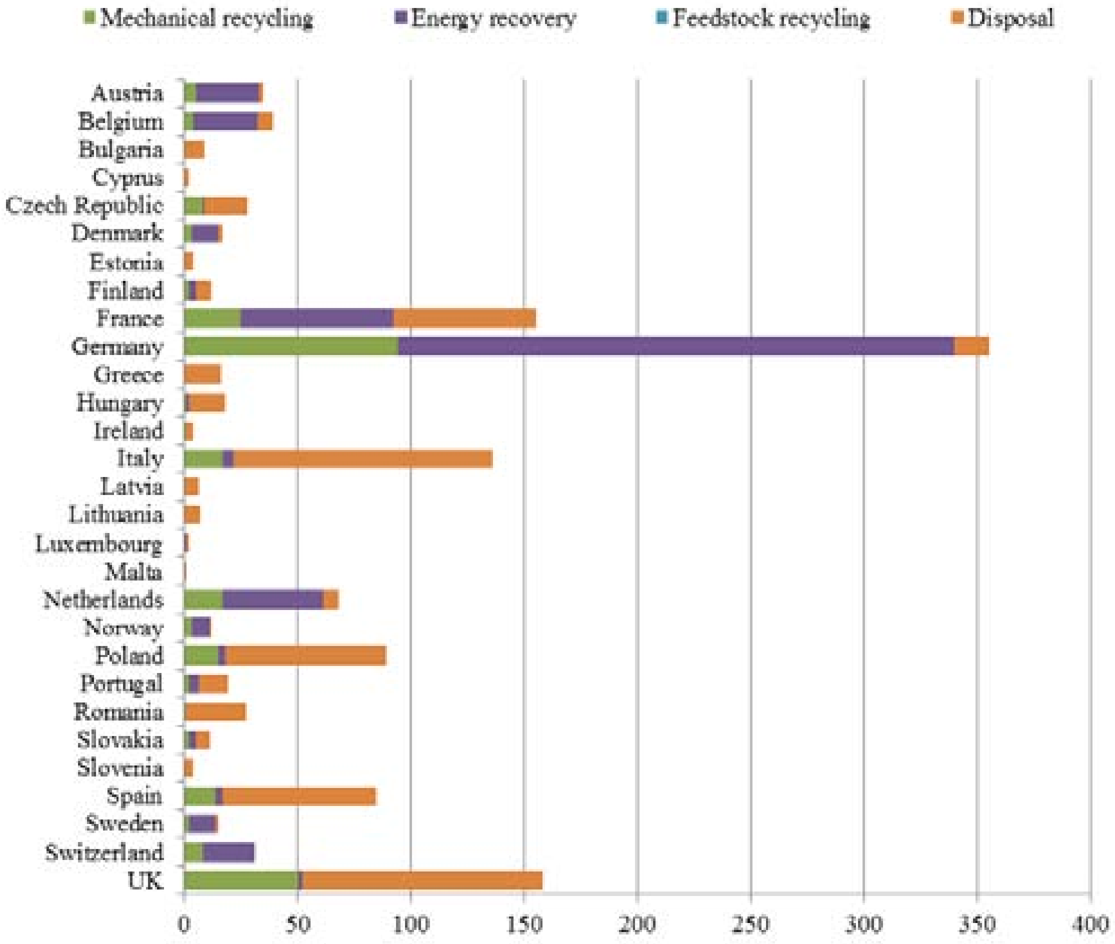


Figure 4.1: Recovery and disposal of construction plastic waste in Europe in 2010. All numbers are in kilotonnes (kt) (Data source: ECVM 2010).

The Waste Framework Directive, 2008/98/EC, aims to protect human health and the environment against harmful effects caused by the collection, transport, treatment, storage and landfilling of waste. The Directive sets new recycling targets to be achieved by the EU Member States by 2020, including 70% recycling rates for construction and demolition waste excluding excavation materials and hazardous waste. The Directive will therefore have an influence on the disposal of plastics used in the construction sector.

In this study, ELCA methodology has been applied to polypropylene (PP) and polyvinyl chloride (PVC), two widely used plastic materials in construction applications, as a case study in a cradle-to-grave life cycle approach. The ELCA is applied not as a substitute for LCA but rather an improvement options for potential exergy efficiency improvements of systems. The purpose of this analysis is to give the reader a better understanding how efficiently resources are used during the life cycle of PP and PVC. The results from this analysis will provide deeper insights into resource use efficiency for the selected materials and will thus offer opportunities to improve process efficiency though reduced exergy loss.

4.2 Materials and methods

The exergy efficiency, e_2, of a system is the relation between the products' exergy and the input exergy. It can be calculated as the useful product output divided by the total exergy input of a process, as expressed in equation 4.1 (Szargut et al. 1988).

$$e_2 = \frac{E_{x,\,product/s}}{E_{x,\,materials} + E_{x,utilities}} \tag{4.1}$$

where, $E_{\mathrm{x,materials,}}$ $E_{\mathrm{x,product/s}}$, and $E_{x,\mathrm{utilities}}$ are the exergy of input materials and utilities, respectively; utilities include water, steam, electricity, and fuels required for the process.

Exergy efficiency calculation requires detailed and disaggregated analysis of material and energy input to each process step of a production chain. Based on simple chain or branched chain production process, the exergy efficiency of the whole process can calculated as explained by Ayres and colleagues (1981). Exergetic efficiency of crude oil and natural gas extraction and processing, resin manufacturing process, and mechanical recycling of PP and PVC waste have been estimatedcalculated using equation 4.1. This study does not include indirect exergy consumptions associated with the materials and utilities necessary for manufacturing of fixed capitals, such as machineries and production facilities. From life cycle perspective, it would generally be favorable to increase the amount of recycled plastics entering new life cycles. Among the three different recycling or recovery processes (mechanical, feedstock, and energy recovery), mechanical recycling (which loops the material back directly into new life cycles) is the European plastic industry's preferred recycling techniques (ECVM 2010). To certain extent, this technique substitutes the processes of resource extraction, intermediate production, and polymerization during the production of virgin material. Thus, this study focuses on mechanical recycling to account the exergy efficiency of recycling process. Exergetic analysis requires quality data on chemical exergy of materials and utilities involved in the process, and a proper mass balance of the process. Published literature data are used to account material and energy balance for unit processes of the case study materials. Table 4.1 illustrates the data sources used in this study.

Table 4.1: Data sources related to the ELCA of PP and PVC.

Parameter	Data source
Extraction and processing of crude petroleum and natural gas	Franklin Associates 2010
Transportation of petroleum and natural gas through pipeline	Dincer and Rosen 2007 ; Franklin Associates 2010
Chemical exergy of materials and utilities involved in the production of PP and PVC	Ayres and Ayres 1999; Szargut et al. 1988
PP and PVC resin manufacturing process	Ayres and Ayres 1999; EuPR 2010; Ren et al. 2004
Recycling of PP and PVC	Al-Salem et al. 2009; Dewulf and Van Langenhove 2004; Hopewell et al. 2009; Sadat-Shojai and Bakhshandeh 2011

4.3 Case studies

Consumption of plastic materials is becoming popular mainly because of their stability and long life, 10-50 years of life time depending on the types of use (PlasticsEurope 2010). In addition, these materials require minimum care and maintenance during the use phase. Plastic manufacturing processes consist of various industrial segments and are related in a complex manner. For example, chlorine, a major raw material for PVC, is manufactured by the soda industry and then converted to PVC by the plastics industry via vinyl chloride monomer (VCM) production. Energy resources, raw materials, and manufacturing processes used in plastic manufacture vary from country by country depending on the availability of feedstock materials and energy sources. Plastic resin production from virgin resources is analyzed in this study in order to assess the overall life cycle exergy efficiency.

4.3.1 Polypropylene (PP)

PP has become one of the most versatile bulk polymers due to its good mechanical and chemical properties. Global consumption of PP in 2010 is estimated 48.4 million tonnes with global capacity utilization 82%. In recent years, PP consumption in the construction sector is increasing especially for piping and fittings. Other uses include window profile, wall covering, and filler fibers in concrete production. It is produced in a low-pressure process, polymerized from propylene. Ethylene and propylene are co-produced by cracking naphtha or gas oil in a steam-cracker (Narita et al. 2002). For PP production, many different polymerization processes exist, such as solution polymerization, bulk polymerization in liquid propylene, and several gas-phase processes. Exergy flows in the production of 1 kg virgin PP is illustrated in figure 4.2. Assuming a branched chain production process as explained by Ayres and Ayres (1999), exergy efficiency of PP production process is estimated 53.4%.

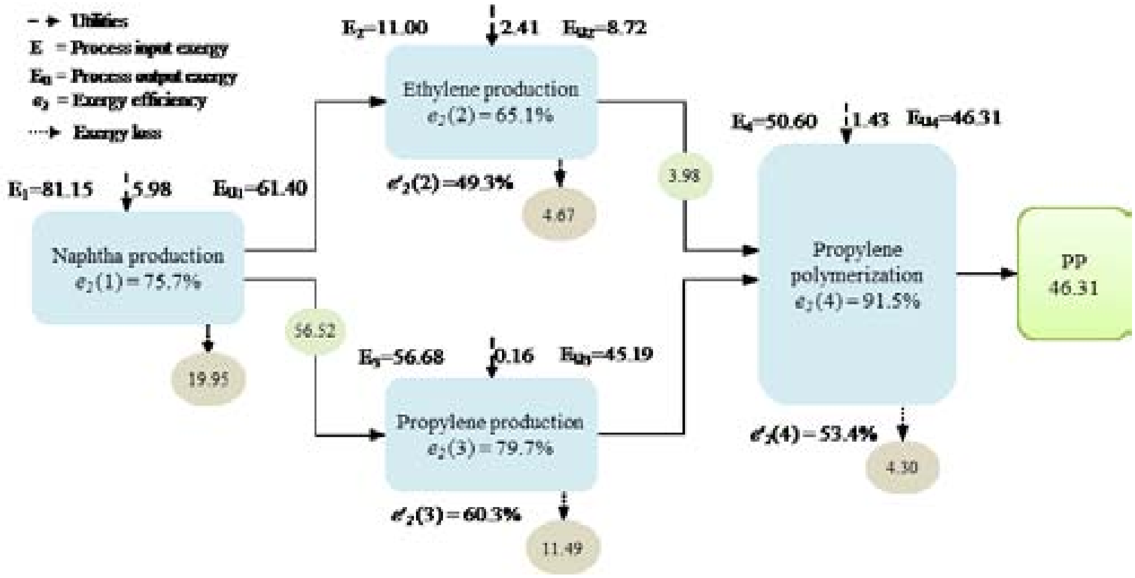


Figure 4.2: Exergy flows (MJ) in the production of 1 kg PP.

One of the major problems of recycling plastic waste is greater inhomogeneity of the polymers present in the waste. However, it is noticed that recycling systematically generates higher output compared to primary production process. It is assumed that 1 kg of PP recycling require 13.44 MJ of utility (including transport and processing) (Dewulf and Van Langenhove 2004), representing exergy efficiency of 70.4% (figure 4.2).

4.3.2 Polyvinyl chloride (PVC)

Pure PVC is hard, brittle material which degrades at around 100°C and is sensitive to deterioration under the influence of light and heat. Pure PVC is therefore supplemented with additives which improve its service life properties and allow it to be processed. Use of pure PVC in building materials depends on the product characteristics and varies 35-98% (PlasticsEurope 2010). Nearly 57% of the total PVC consumption goes to the construction industry. Global demand of PVC is expected to an average growth of around 4.7% per year from 2010 to 2015, and 4.2% from 2015 to 2020 (PlasticsEurope 2010). PVC production is more complex rather than that for PP, because the processes involve multiple reactions such as naphtha to ethylene, ethylene to ethylene dichloride (EDC) followed by vinyl chloride monomer (VCM) production, and PVC from VCM polymerization. EDC is one of the precursors for VCM in direct chlorination process. It is assumed that HC1 generated from thermal decomposition of EDC is used as the raw material for the oxy-chlorination process. Exergy flows in the production of 1 kg virgin PVC resin is illustrated in figure 4.3, from which the overall exergy efficiency is accounted for 23.7%.

Due to the high chlorine content, some of the recycling techniques are not favorable for PVC. In particular, landfilling and composting are not suitable because of known and unknown hazards associated with the oxidative degradation of PVC in the environment. Incineration and pyrolysis may also be disfavored because of the production of large amounts of hydrogen chloride and other toxic chemicals. Thus, mechanical and chemical recycling are the two main processes of PVC recycling, the former is preferred when the provenance of PVC waste is known. This study calculated the exergy efficiency of mechanical PVC recycling, of 54.2%, assuming an average yield of 90% PVC (Shonfield 2008).

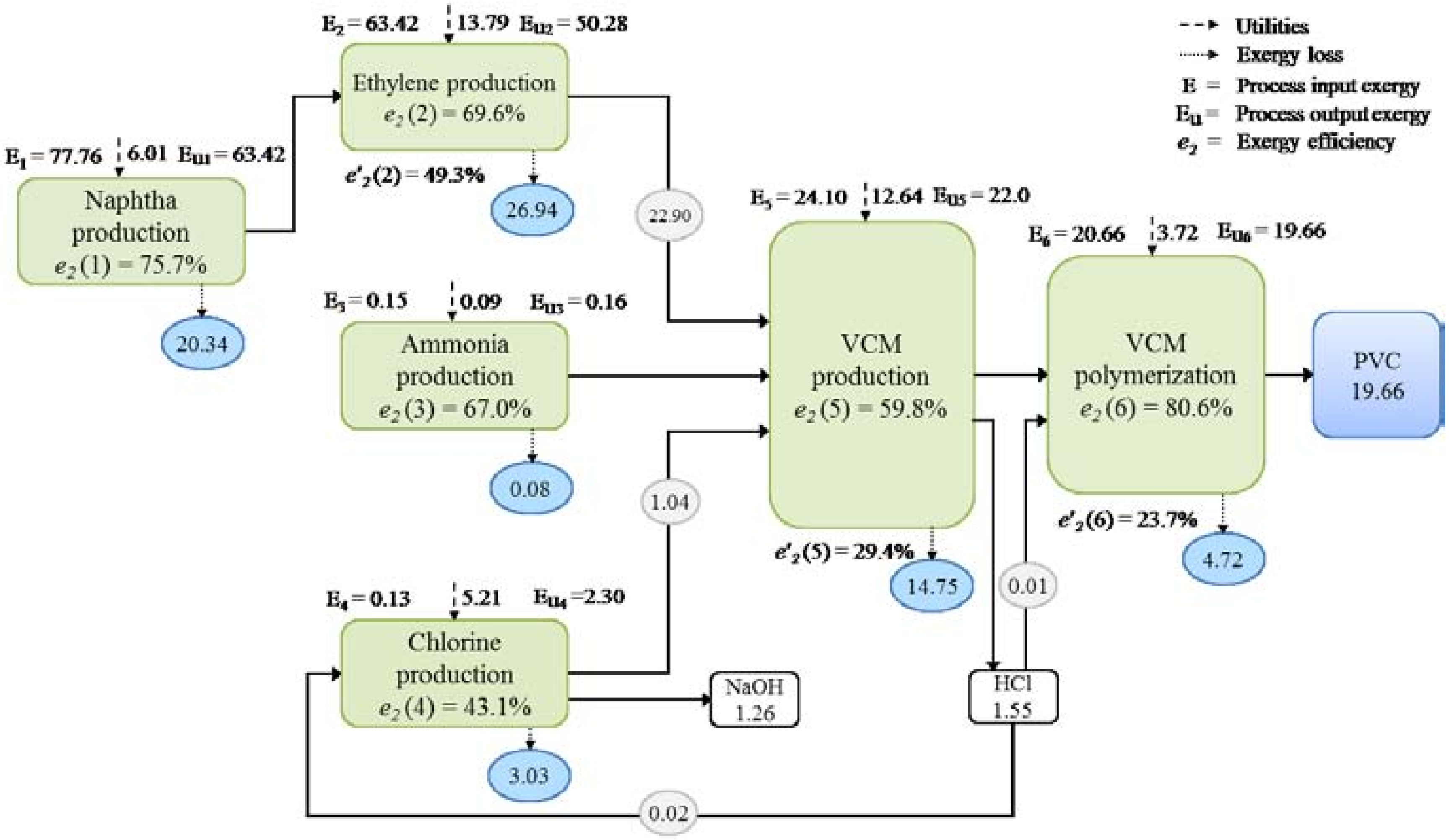


Figure 4.3: Exergy flows (MJ) in the production of 1 kg PVC.

4.4 Results and discussions

The study shows that within the PP and PVC chains, the resin production plays a major role in overall resource use efficiency. Exergy consumptions associated with manufacturing processes are relatively high and major inefficiency takes place in the production stages for both PP and PVC. This study used 1MJ of electrical energy equals 1MJ of exergy in this analysis (Szargut et al. 1988). However, if the efficiency of electricity production was considered (assuming 31.8% efficient; Dincer 2002), the manufacturing or recycling efficiency would be even lower. For example, exergy efficiency of PVC and PP production becomes 20.0% and 50.1%, respectively, considering the electricity production efficiency. Exergetic efficiency of different life-cycle stages of PP and PVC is illustrated in figure 4.4, representing the overall life cycle efficiency of PVC and PP, 9.3% and 27.1%, respectively. Thus, PP has better exergetic efficiency for both production and recycling processes. On the other hand, the gross CO_2 emission from the manufacture of plastics is 1.4 and 1.7 kg-CO_2/kg-PP and PVC, respectively (Franklin Associates 2010; Shonfield 2008). Improving process efficiency will thus reduce the cumulative exergy consumption throughout the material life cycle and associated carbon emissions.

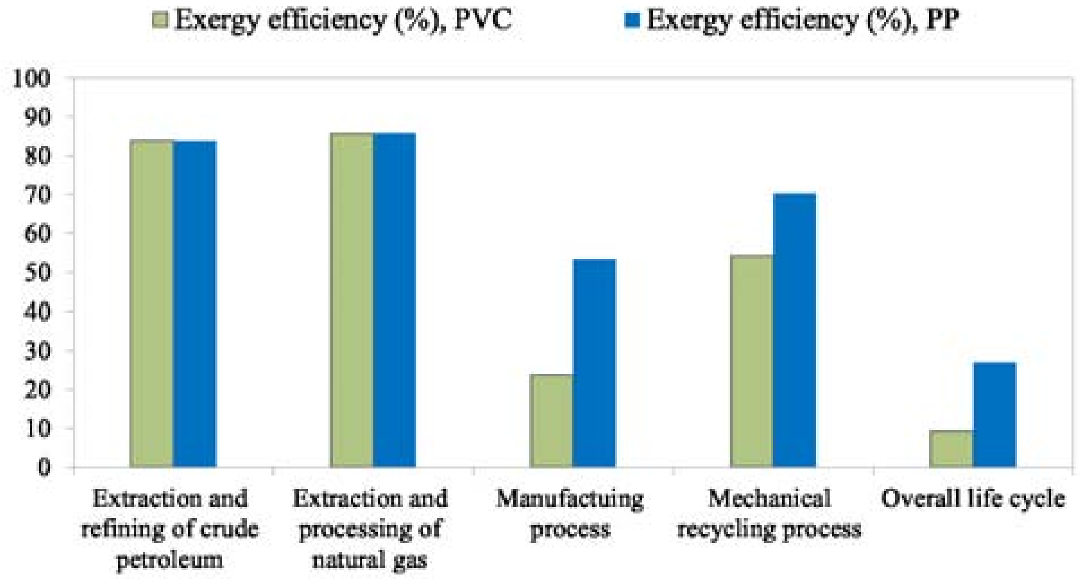


Figure 4.4: Exergy efficiency of overall life cycle and different life-cycle stages of PP and PVC.

The figure demonstrates that the exergy efficiency of extraction, refining/ processing, and transport life cycle stages is much higher compared to manufacturing and recycling processes (see appendix C for detailed calculation). Improvement opportunities can be assessed comparing the efficiency outcomes of the processes analyzed with the theoretical exergy efficiency. As an example, theoretical exergy efficiency of VCM production from ethylene, which is an exothermic reaction (equation 4.2), is 91.9%; whereas, in present industrial practice the said efficiency is 59.8% (figure 4.3).

$$CH_2{=}CH_2 + Cl_2 \rightarrow CH_2{=}CHCl + HCl + 16.4kJ \qquad (4.2)$$

Therefore, it is logical to conclude that significant exergy improvement opportunities still exist but requires process optimizations.

Mechanical recycling is being used for 35.5% of the total plastics waste recovered in the EU27+2 in 2010 (ECVM 2010). This technique directly recovers clean plastics for reuse in the manufacturing of new plastic products. The difficulties of plastic recycling are mainly related to the degradation of recyclable material and heterogeneity of plastic wastes (Perugini et al. 2005). Mechanical recycling can only be performed on single-polymer plastic. The more contaminated the waste, the more difficult it is to recycle it mechanically. Separation, washing, and preparation of plastic waste are all essential to produce high quality, clean, and homogenous end-products (Al-Salem et al. 2009). Both mono and composite fractions can be collected separately from the waste stream by sorting. For mixed and composite plastic wastes, a suitable feedstock recycling process can be developed. By definition, energy recovery implies burning waste to produce energy in the form of heat, steam, and electricity. This is only considered a sensible way of waste treatment, when material recovery processes fail due to economical constrains.

4.5 Conclusions

Increased efficiency preserves exergy by reducing the exergy necessary for a process, and therefore reduces environmental damages. The results obtained from this analysis show that the exergy efficiency of manufacturing and recycling processes are low compared to raw material extraction and processing for both PP and PVC. Comparing the results of this analysis with the theoretical minimum exergy required in different life-cycle stages will offer the improvement potentials of the processes. The material choice can be discussed depending on the ELCA results as it is a straight-forward parameter that can easily be communicated even though within ELCA, material choice is simply one parameter among many inter-dependent parameters. In addition, the results of this analysis can also be compared with other quantitative tools covering the technological aspects such as social, financial, and environmental parameters to strengthen sustainable resource use.

CHAPTER 5

Discussion, Conclusions, and Future Research

5.1 Discussion

In this chapter, a synthesis of this PhD is accomplished summarizing the main results both at macro and micro levels. This chapter starts with a general discussion of resource accounting within the construction sector, highlighting limitations and potential challenges to achieve improved sustainability of this sector. Then, the results of this thesis have been discussed addressing three main aspects namely: material and exergy flows in the Catalan construction sector; exergy efficiency of material manufacturing; and life cycle exergy efficiency of materials followed by scientific contributions and overall conclusion. Finally, the perspectives of future studies that have arisen from this PhD are presented.

5.1.1 Resource accounting within the construction sector

Accounting for resources (energy and materials) within the construction sector is motivated by a desire of improved resource management since their abundance is limited in the nature and consumption of bulk materials generates wider impacts in the society and the environment. Over time, it is gradually recognized that the lack of systematically organized data, together with simplified assessment tools are the main obstacles to a satisfactory resource management in this sector (Alfsen 1996). Therefore, more emphasis is now put on trying to integrate environmental and resource utilization issues within the economic planning tools, highlighting the linkages between economic development, natural resource use, and environmental concerns. Due to scarcity of non-renewable resources, the construction sector requires an efficient biophysical assessment with overall and unified accounting.

The overall stock of construction materials within the economy is growing, embodied in buildings and infrastructures, most of these are construction minerals (asphalt, cement, sand and gravel, crushed stone, and other aggregates), metals, ceramic, glass, and plastics. On the other hand, the stocks of the construction sector in many countries, regions, and cities are ageing. Thus, there is a growing need for optimized resource management in order to minimize future waste and take advantage of the generated waste from this sector. Figure 5.1 represents the age of dwelling stock in Catalonia, Spain, Denmark, and Finland; showing that 10-31% of the existing stocks has already crossed their expected life span (assuming 70 years of service life). It is obvious that these stocks will turn into waste in the coming years. However, accounting for these possible future resources are difficult due to the limited historical data availability of the existing stocks based on the characteristics of materials and construction itself.

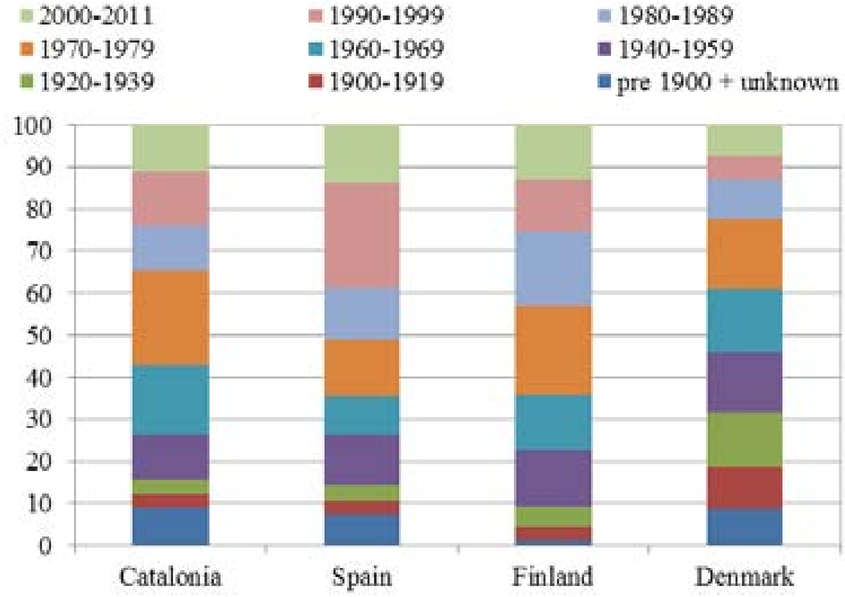


Figure 5.1: Age of dwelling stock in Catalonia, Denmark, Finland, and Spain.

[*Age classification of the stock in Catalonia and Spain: pre 1900, 1900-1920, 1921-1940, 1941-1960, 1961-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2011.*
Data source: Catalonia and Spain-INE 2011; Denmark-Statbank 2011; Finland- StatFin 2011]

The role of the construction sector in minimizing environmental burden is crucial. It is well known that the construction sector is one of the largest contributors of GHG emissions, accounting for 30% of global carbon dioxide emissions (UNEP 2009). Apart from emissions, construction and demolitions waste (CDW) represents the major waste streams in the economy (EC 2012). Thus, introducing IE concept in resource management of this sector provides deeper insights into sustainability since the closed-loop concept combines the aims of zero waste and improved resource-efficiency (Sassi 2008). From these perspectives, this thesis has applied MFA and exergy-based methodologies in order to assess the sustainability of the construction sector. Based on the mass balance principle, resource (both energy and material) inputs and outputs of the Catalan construction sector have been estimated for 2001. Quantified the CDW generation and their composition have been carried out based on assumptions and available literature data.

5.1.2 Limitations in resource accounting within the construction sector

It is recognized that there is a clear lack in data inventory since standardization is poor within the construction sector. Due to its complex nature and long life span, readily available quality international datasets are not available for construction sector. As a result, resource accounting within this sector is difficult, based on assumption and/or estimation, and thus the assessment results are not easily comparable. Currently, available datasets are typically not transparent, and most of these inventories are based on simple materials but not for the complex ones such as metal alloys, wood plastic composites, paints, plastic materials etc. To avoid large uncertainty in the assessment results, the scope of this thesis has been limited to material with reliable industry data and available published literature data on processes based on degree of disaggregation.

MFA provides important information on the amount of materials involved, and waste and emissions generated from a system. However, it fails to address environmental impacts associated with resource use. Besides, MFA results are demonstrated in various units (energy, mass, monetary) based on input-output (IO) tables. A common problem associated with the use of IO table is that energy supply sectors are often aggregated either with non-energy supply sectors or other energy supply sectors (Acquaye and Duffy 2010). For instance, petroleum and other manufacturing sector is an aggregation of an energy supply sector. National average energy tariffs can be used to convert economic data to energy consumed, although such conversion may provide over or under estimated values. Another difficulty of using IO table is the total energy inputs include energy inputs for imported goods and services. Consequently, there is always a possibility of double counting since the energy use of imported goods and services can be counted in exporter country.

LCA is unanimously considered as the reliable tool for environmental performance assessment of construction. However, its everyday use by non-experts in construction or refurbishment projects is limited due to several scientific and technical limits such as defining system boundary, large inventory data, various assessment methods, complex interpretation of results etc. Besides, LCA generally considers buildings as objects neglecting the fact that buildings can also be considered as a service. In the later case, functional units can be changed to time of occupation, the number of persons per surface, and the interior climate (Kohler 2012). The long lifetime of buildings also distinguishes them from manufactured objects. Thus, problems associated with LCA application can be grouped into mainly 4 domains: (i) the availability of standardized basic data both for materials and processes; (ii) assessment methods which include functional units, rules, considered effects and indicators; (iii) system representation and allocation rules; and (iv) life cycle scenarios including service life assumptions, replacement scenarios, changing technologies.

5.1.3 Challenges in achieving a sustainable construction sector

Non-renewable natural resources are limited and thus their management must be carefully planned to achieve sustainable construction sector. However, it is simply impossible to manage the resources effectively if we do not know what quantity is available, at which rate these are depleting, and how efficiently they are utilized in construction applications. Thus, accurate resource accounting is crucial in order to develop strategies for sustainable resource management of this sector. One of the major challenges at this end is to simplify information relating to products’ lifecycle to make it more accessible and easily understandable, delivering a well-defined balance between the need and objectives of resource accounting. Life cycle data of products, providing useful and accurate information, can be costly and time consuming. However, using generic data and information in a specialized application could lead to a wrong choice (Liao et al 2012). Besides, some of the economic values have a considerable dynamic variation, such as the price on transportation, which shifts with fuel prices. One of the solutions at this end can be to use historically observed data and correction of data based on the corresponding statistical index.

Even though more than 95% of the CDW are reusable or recyclable, demolition activities are not systematically planned in most of the cases to recover valuable materials and bring back to their new life cycle. A “soft” demolition technique can be used in order to maximize the recovery of materials for reuse and recycling. Some of the construction materials are difficult to recycle due to chemical change or quality degradation such as cement, latex paint, chemical solvents, and adhesives. However, assuming construction sector as a large system, most of these materials can be reused or recycled except hazardous ones such as asbestos. Design for disassembly and use of relatively pure form of material can facilitate and promote enhanced reusability and/or recyclability in this sector.

Recycling systems are often complicated both for the estimation of value-added and for environmental influence, and allocation problem (Bohne et al. 2008). It is a challenge to make use of appropriate system borders, cut-off rules, and allocation rules when dealing with CDW. The forecast for building waste is highly problematic because the basic data of present waste are not reliable and nearly complete lack of data on renovation (Kohler and Hassler 2002; Reinhart et al. 2003). It is important to justify which materials can lead towards best recycling benefits, and E_xA offers effective solutions in that perspective since this tool is capable of assessing the process inefficiencies. Consequently, process improvement potentials can be determined with this tool. In addition to that, stakeholders such as manufacturers, practitioners, designers, architects, contractors need to be involved to products' life cycle issues instead of only economic values.

5.1.4 Synthesis of the dissertation

The aim of this PhD has been the assessment of the resource metabolism of the construction sector applying material and exergy flow analysis. The main advantage of using exergy with respect to other physical indicators is that all the physical features of a resource are accounted for in a single property with the capability of aggregating heterogeneous energy and material resources. Unlike standard economic valuations, the exergy analysis gives objective information since it is not subject to monetary policy, or currency speculation. This thesis has been structured mainly into two different parts. The first part has described the theoretical framework under which exergy and material flow analyses are used in assessing the resource metabolism of the construction sector. The second part has developed and used the exergy tools required for analyzing the state of this sector.

In ***chapter 2***, a comprehensive analysis of the physical flows of the Catalan construction sector in 2001 has been undertaken as a starting point to determine the inputs and outputs using MFA and E_xA methodologies. This overview provides detailed explanation on the interactions of materials among different sub-systems such as extraction from natural environment, material manufacturing and/ or processing, transport, imports and exports, and CDW recycling. This case study has quantified 75% of the extracted minerals are used in construction applications either as direct consumption or as raw material to produce cement, concrete, mortar, ceramic, glass, and other mineral processed materials.

It has been observed that non-renewable materials account for more than 98% of the input materials in the sector. Therefore, the management of construction materials should be carefully planned both in pre- and post-construction levels. Even though the buildings are responsible for diversified material use compared to infrastructure, including structural and civil constructions, the study has identified that 59% of the total used materials have been consumed in the construction and maintenance of infrastructure. Apart from material consumption, the sector has generated nearly 6.8 million tonnes of CDW, of which only 6.5% have been reused and/or recycled. Thus, there is enough room to potentially improve the material management in the Catalan construction sector. Recent study shows that the Catalan construction sector has improved the recycling activities, but still far behind the target set by European Waste Framework Directive, 70% recycling of CDW excluding excavation hazardous materials by 2020. Figure 5.2 shows the recycling trends of CDW in Catalonia from 2001-2011. Even though the recycling percentage has virtually changed in recent years (from 6.5% in 2001 to 49% in 2011), in absolute quantity of recycled materials is nearly unchanged between 2005 and 2011.

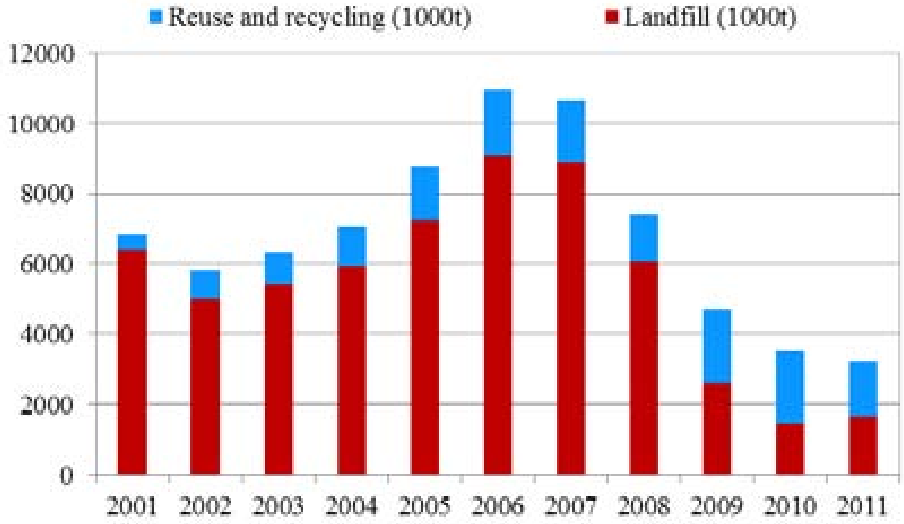


Figure 5.2: CDW recycling in Catalonia from 2001 to 2011. *Data source IDESCAT 2011*.

This case study has applied exergy tool to quantify the energy intensity of construction materials, using mass balance principle from life cycle perspectives, and has presented the exergy balance of the Catalan construction sector demonstrating how E_xA together with MFA can provide better insights into resource conservation overview. The results show that energy intensive materials such as bituminous mix products, ceramics, glass, metals, plastics, and wood products account for 69% of the total exergy input (113.1 PJ) in the sector, even though these materials represents only 15% by mass. The analysis has also estimated that with a recycling rate of 6.5%, the sector have recovered 1.3 PJ of exergy, however with a recycling rate of 80%, the exergy recovery could reach 10.3 PJ (nearly 9% of the total exergy input in the respective year).

Since the aseeesment of resource use efficiency requires the knowledge of material manufacturing efficiency, this thesis has estimated the exergy efficiency of major non-renewable construction materials in *chapter 3*. The objective of this case study is to assess the manufacturing inefficiencies in present industrial practices demonstrating the improvement potentials of the case study processes. Exergy efficiency alone is not sufficient for an effective evaluation of technologies and thus this study has presented theoretical exergy efficiency, based on theoretical minimum exergy demand for processes, offering improvement potentials of material manufacturing. For that purpose, a revision of the studies concerning the material manufacturing process has been carried out. The exergy efficiency estimation has been performed based on gate-to-product life cycle perspectives. Both primary and secondary production processes are assessed in this study in order to address the potential benefits of recycling. It can be stated that the heterogeneity and complexity of current manufacturing processes have hindered accurate exergy efficiency of the case study materials. However, widely used manufacturing technologies of the case study materials, and material and energy use in each process steps of these technologies have carefully been assessed to avoid uncertainty in estimations.

The results of this study show that some of the present industrial processes, such as copper, ceramic, and glass, are highly inefficient and theoretical exergy efficiency results (see table 10 in chapter 3) suggests that enough room for process improvements still exists. For instance, exergy efficiency of primary copper production process is quantified 1.8%, whereas the theoretical exergy efficiency is estimated to 50.9%. Thus, this process has an improvement opportunity of 49.1%. This estimation includes sulfide copper ore concentration, roasting and smelting of concentrate, H_2SO_4 production, oxide copper ore concentration, and electrolytic refining steps. Among these steps, ore concentration process steps are found to be highly inefficient since copper ores typically contain 0.5-

1.0% Cu, making primary copper production highly exergy intensive. Aluminum and iron on the other hand represent second and third most abundant elements in the earth's crust, respectively. Alumina content of aluminum ore (bauxite) ranges from 31-52% (OECD 2010) and iron content of iron ore (hematite, magnetite, and limonite) ranges from 40-59% (AMA 2012). As a result, these metals are assumed to be less exergy intensive compared to copper which is also reflected from the results of this study (table 5.1), showing total exergy input in the primary production processes of steel, aluminum, and copper is 31.54, 128.52, and 236.22 MJ per kg of output, respectively.

It is clearly evident from the table 5.1 that recycling can potentially transform the current inefficient industrial sector to an efficient one since recycling processes (secondary production process) have the potential to save from 25.2% (glass) up to 96% (aluminum) exergy inputs in the production process.

Table 5.1: Exergy inputs from energy sources in primary and secondary production processes for 1 kg product output based on present industrial practices.

Material	Exergy input in primary process (MJ)[a]	Exergy input in secondary process (MJ)[b]	Difference in input exergy (MJ)[c]	Exergy savings in secondary process (%)[d]
Steel	31.54	11.7	19.84	62.9
Aluminum	128.52	5.15	123.37	96.0
Copper	236.22	6.3	229.92	97.3
Glass	8.54	6.36	2.18	25.2
PP	83.57	13.4	70.17	84.0
PVC	63.67	13.4	50.27	79.0

*Note: c = a-b, d = c/a*100; cement, concrete, and ceramic are excluded from this table, since it is assumed that cement cannot be brought back to its original state through recycling process, and the recycling outputs of concrete and ceramic are considered as aggregates in this study.*

Exergy efficiency of primary steel production process has been quantified 16.3% assuming a branched chain production process, whereas theoretical exergy efficiency is estimated to 56.3%. Agglomeration processes (pelletizing and sintering), used to meet the specific characteristics required for blast furnace feed, are characterized as low efficient process steps in primary steel production chain. The exergy losses in these steps are mainly because of the application of high temperatures and the need for several cooling and reheating steps. Irreversibilities associated the heat transfer and some undesired chemical reactions only occur at higher temperatures such as nitroden oxide (NO_x) and zinc ferrites ($Zn_xFe_{3-x}O_4$), contributing to these exergy losses. De Beer and colleagues (1998) has quantified that introducing heat recovery techniques and applying recovered heat to preheat raw materials can reduce up to 2.5 MJ of exergy per tonne of crude steel production.

Even though the theoretical and empirical exergy efficiency results of Bayer (24.8% and 10.1% respectively) and Hall-Héroult processes (91.7% and 36.7%, respectively) suggests that the primary aluminum production process can be potentially optimized, further improvement of these processes may not be economically and technically feasible since these techniques require high energy and electricity consumptions for process heating (Bayer) and electrolytic smelting (Hall-Héroult). Besides, a significant portion of the input chemical exergy in Bayer process is embodied in the red mud waste (nearly 43% Fe_2O_3).

Presently more than 90% of aluminum is recycled from construction applications. The advantage of scrap recycling is that it requires significantly less energy (nearly 5.1 MJ/kg) compared to primary production process (105.9 MJ/kg). Besides, current aluminum scrap recycling is a highly efficient (82.9%) technique and has become more popular compared to primary production.

Clinker is the major constituent of Portland cement, and in this study exergy efficiency of CEM I Portland cement has been assessed assuming a mixture of 95% clinker and 5% gypsum. The results obtained from this analysis show that exergy efficiency of cement production in actual industrial practice is 12.6%, whereas theoretical efficiency is 34.1%. The low exergy efficiency of cement production is associated with exergy losses due to irreversibilities in raw feed preheating and clinker cooling. Exhaust heat recovery from the kiln, utilizing to preheater and/or calciner for the raw materials can potentially improve cement production efficiency. Apart from heat recovery, alternative material and fuel use also can improve the efficiency cement production process. The former involves use of reducing the amount of clinker in the finished cement, known as clinker factor reduction or material substitution. There are two main alternatives to clinker in cement: blast furnace slag and pulverized fuel ash or fly ash. Alternative fuels include organic waste, animal feed, and biomass.

Concrete is widely recognized as a sustainable building material when both energy consumption during its production and inherent properties are taken into account. However cement, the main ingredient of concrete, contains significant embodied exergy and cement manufacturing is recognized as exergy intensive process as well as a major source of carbon dioxide (CO_2). Assuming a simple chain production process, the exergy efficiency of concrete production is accounted for 9.5%. Theoretical minimum exergy demand to produce concrete is the exergy demand, to mix the ingredients, is calculated 0.027 MJ/kg. With this estimation, theoretical exergy efficiency of concrete production is calculated 26.9%. It is to be mentioned that there is a limited scope to improve the efficiency of concrete production without increasing cement production efficiency since mixing process to produce concrete has an exergy efficiency of 75.2%, while theoretical limit of that is 78.8%. Concrete recycling has gained great importance in recent years. Recycling protects natural resources though minimizing the extraction and eliminates the need for disposal by using it as a source of aggregate material for new concrete production or for road base.

This study analyzes the exergy efficiency of ceramic tile manufacturing. In the development of ceramic properties during firing of ceramic body, the most important change involves the breakdown of lattice structure of the clay minerals to form new crystalline structure or glassy phase, which require high temperature nearly 1300°C, making ceramic production process highly inefficient (4.6%); whereas theoretical exergy efficiency of ceramic tile production is estimated 39.4%. Thus, heat recovery can be a potential step change in current ceramic production process. Post-consumer ceramic tiles cannot be recycled but can be use as a source of aggregate. In this study, theoretical and practical exergy efficiency of ceramic tile recycling has been estimated 26.1%and 25.0%, respectively assuming no loss of material while crushing process.

Glass melting energy demand accounts for more than 75 % of the total energy use in glass manufacturing process. The large inefficiency in glass production is because of exergy destruction for fuel combustion and heat transfer process, representing together nearly 50% of the total exergy inputs. Up to 30% of the heat from melting is expelled through the exhaust gases and furnaces equipped with regenerators or recuperators recover some of this heat, which can potentially be used to preheat the batch or cullet. Exergy efficiency of flat glass production is estimated 11.5% in actual industrial practices. Theoretical minimum exergy demand is calculated based on the heat of reaction for glass formation plus thermal energy required to raise the temperature to 1550ºC, is 2.38 MJ/kg. This estimation gives the theoretical exergy efficiency of glass production 36.7%. While calculating exergy efficiency of recycling process, it assumed that 30% of cullet is used in the recycling process in order to quality output with desired properties. With this estimation, exergy efficiency of glass recycling is calculated 14.2% in actual industrial practice and 35.7% in case of theoretical efficiency.

The results of this study clearly demonstrates that exergy resources are utilized very inefficiently in present industrial practices since energy intensity of most of the case study processes is significantly higher than the theoretical minimum determined by the second law analysis, from 10% (PP) to 304% (copper) (see table B.6 and B.7 in the Appendix B for detailed calculation). These estimations have been performed assuming the final energy consumption in the processes, which means energy consumption to produce the final energy is not considered throughout the analysis. For instance, average exergy efficiency of electricity production is reported 31.8% in literature (Dincer 2002). However, this study considers 1MJ of electricity equals 1MJ of exergy. Thus, some exergy efficiency values represent overestimation, especially the ones use electricity as the major source in their production process such as steel production in EAF.

Table 5.2 illustrates the exergy efficiency of case study materials for both primary and secondary production processes in current industrial practices, including theoretical exergy efficiency of the respective processes. It also represents a comparison of the results obtained from this study with the ones available in literature. These exergy efficiency results, comparing with the theoretical ones, showing that there is ample room exists to optimize the present industrial processes of the case study materials. Apart from estimating the improvement potentials, this study also presents an example on how introduction of achievable new technology, using Boehmite process instead of Bayer process, can improve the exergy efficiency of primary aluminum production delivering significant energy savings in present industrial sector. The Boehmite process uses similar process flow like the Bayer process but replaces gibbsite seeding with boehmite seeding, and an optimization can be achieved through precipitation of monohydrate (boehmite) rather than trihydrate (gibbsite) alumina under atmospheric pressure in temperatures lower than 90°C (as presented in chapter 3). The entire alumina production process utilizing the Boehmite process, when compared to the conventional Bayer process, can achieve 19% energy savings and 2% increase in the exergy efficiency. Another approach to optimize the process efficiency is to utilize the high exergy embodied red mud waste instead of sending to landfill. The relatively high exergy embodied in the red mud is mainly due to its high content of Fe_2O_3, which could characterize red mud as an industrial feedstock rather than an industrial waste.

High temperature Carbothermic reduction is a direct chemical reduction of alumina to aluminum, an alternative to the electrolytic reduction. The main exergetic benefit from replacing the electrolytic reduction of alumina with a Carbothermic process is that carbon will be used as a direct reducing agent supplying the 47% of the total energy for the process instead of the 8% that is currently being utilized as consumable carbon anodes. The high exergetic cost of transforming carbon into electricity to drive the redox reaction will be avoided, while the alumina reduction will take place in a three-dimensional space thus avoiding heat losses due the volumetric inefficiency of the Hall-Héroult process.

Table 5.2: Estimated process exergy efficiency of the case study materials and comparison with available literature values.

	Result estimated in this study (%)														
Material	Primary (industrial)	Primary (theoretical)	Secondary (industrial)	Secondary (theoretical)	[1]	[2]	[3]	[4]	[5][1]	[6]	[7,8]	[8,9]	[8,10]	[11]	[12]
Aluminum, primary	10.8	22.7	82.9	92.5		24.40		30.17[2]; 14.05[3]				13.20-16.60	32.60		
Copper	1.8	50.9	22.9	70.7		10.26							9.20		
Steel	16.3	56.3	35.6	81.8		23.40						40.10			28.60
Iron and steel					46.00									48.00	
Iron, BF															53.10
Cement	12.6	34.1										10.10-17.00			
Concrete	9.5	26.9	67.8	75.9											
Ceramic	4.6	39.4	25.0	26.1											
Glass	11.5	36.7	14.2	35.7			2.9[4]						22.10		
PP	54.6	60.8	70.4	90.3					60.2	54.50	58.60				
PVC	25.2	52.3	54.2	90.5			37.00		24.4	29.00	30.00		90.30[5]		

[1] Al-Muslim Dincer 2005; [2] Ayres et al. 2006; [3] Ayres and Ayres 1999; [4] Balomenos et al. 2011; [5] Dewulf et al. 2010; [6] Dewulf and Van Langenhove 2004; [7] Gaines and Shen 1980; [8] Ayres et al. 2011; [9] Gyftopoulos et al. 1974; [10] Hall et al. 1975; [11] US OTA 1980; [12] Szargut et al. 1988.

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[1] Calculated based on cumulative exergy consumption from the natural environment (CEENE);

[2] Estimation based on final output divided by total input; energy consumption from hydroelectricity plant;

[3] Estimation based on final output divided by total input; energy consumption from coal burning plant;

[4] Estimation based on the consumption of natural gas as fuel;

[5] Calculation based on polymerization process step

Manufacturing process is one of the many steps involved in a products whole life cycle. Even though it is the most energy intensive life cycle stage, a life cycle exergy efficiency analysis can provide deeper insights into overall resource use efficiency of a product in construction applications. In this perspective, the application of ELCA methodology has been assessed in Chapter 4 in order estimate the overall life cycle exergy efficiency of PP and PVC as a case study. The ELCA can examine the exergy flows throughout the life cycle of a product and seeks to reduce exergy destructions, improving the exergy efficiency of complete life cycle processes. This estimation involves extraction and refining of crude petroleum and natural gas, resin manufacturing, and mechanical recycling of PP and PVC waste life cycle stages. The results show that the overall life cycle exergy efficiency of PP and PVC, 27.1% and 9.3%, respectively, characterized by a low exergy efficiency of manufacturing processes compared to other life cycle stages. This analysis concludes that ELCA can be used as an effective tool for material selection in construction applications, providing life cycle exergy benefits of a product.

5.1.5 Scientific contributions of the dissertation

The main scientific contributions generated in this dissertation are:

(i) This dissertation has provided average chemical compositions of the construction materials, including both renewables and non-renewables. Although these information are available in the literature, it is rather dispersed in a significant number of different publications. The integration of all these data accomplished in this work, provides a global overview of the construction materials with special attention to the non-renewables. Besides, standard chemical exergy of these materials has been estimated in order to assess the resource consumption of this sector.

(ii) The study has estimated for the first time the energy intensity of construction material as well as the sector using E_xA methodology. This evaluation has been done based on cradle-to-cradle life cycle perspectives. Assuming the construction sector as a closed system, the mass conservation principle suggests that the inputs (both material and energy) must be equal to the outputs including waste, emissions, and process irreversibilities. Based on this principle, a rigorous analysis of the main materials, more than 100 most commonly used ones, has been carried out in this study. Since different assumptions have been made during calculations, it constitutes the first step for obtaining a coherent and comprehensive energy intensity of construction materials and cannot be used as benchmark value.

(iii) The physical flows of material and energy resources are accounted in terms of mass, volume, monetary, and energy units in the IO tables. This study has comprehensively translated volume and monetary units into mass unit in order to estimate chemical exergy of materials. For instance, monetary unit is translated based on the average price per tonne of material in Catalonia in 2001 for domestically produced materials and average imported price per tonne of material in the same year. With these estimations, this thesis has been able to illustrate for the first time the exergy flows in the Catalan construction sector.

(iv) This study has obtained an inventory of the most important renewable and non-renewable resources of the construction sector in exergy terms. The main novelty introduced in the inventory is the combined assessment of energy resources with nonfuel minerals. Since exergy is an additive property, the thesis has been able to obtain the total exergy inputs of the energy and material resources in the construction sector. With the help of the exergy indicator, this thesis has been able to account the addition to stock in the Catalan construction sector in terms of exergy.

(v) An important advance entailed in this dissertation with respect to the works of Sendra Sala (2008) has been the inclusion of the exergy assessment of natural resources consumed in the construction applicaiton. Consequently, this study has been able not only to calculate what is the energy intensity of materials, but also at which rate these resources are being lost from the sector, and the potential improvement opportunity of material manufacturing. For that purpose, exergy efficiency of materials has been accounted. A number of studies have been undertaken by different authors to assess the production processes of cement and clinker, chemicals, metals, and plastics applying exergy analysis method. However, these studies have presented exergy accounting for individual process or process steps in order to identify major losses and improvement potentials without considering theoretical limits of the respective processes. Besides, the results obtained from different stages of the overall process are not typically combined to give an overall efficiency representation from an exergy perspective. Without such an approach it is not possible to evaluate the actual resource use efficiency and environmental burden associated with the material and energy use in the construction sector. Such a common framework enables the analyst to evaluate the resource use efficiency, not only for a single process or a particular process step but also for the whole sector. Estimating the theoretical exergy efficiency for both primary and secondary production processes, this thesis has been able to assess the process improvement potentials of nine major non-renewable construction materials.

(vi) This thesis has developed a complete thermochemical data set of the main substances that compose the major construction material (see table B.15 in the Appendix B). For that purpose, the standard Gibbs free energy, enthalpy of formation and specific exergy of more than natural substances has been provided. The enthalpy and Gibbs free energy of the compounds have been compiled from the literature, or have been calculated with the estimation methods described by (Valero Delgado 2008). From the Gibbs free energy data and the chemical exergies have been compiled in this dissertation, enabling the estimation of the specific chemical exergy and theoretical minimum exergy demand in processes of the considered materials.

(vii) In addition to the global overview of the state of resource flows in the construction sector and exergy efficieny of manufacturing processes, this dissertation has estimated the possible exergy destruction throughout the life cycle of products. This has been carried out using ELCA tool, which shows the irreversibilities in different life cycle stages of products, including extraction, manufacturing, and waste management of PP and PVC.

5.2 Conclusion

This dissertation presents tools that could aid in the metabolism of energy and material resources within the construction sector. All chapters from 2 to 4, which present research results, have had their own specific discussion and conclusions with recommendations where appropriate. Therefore, this chapter draws the general conclusions and recommendations, based on the information and results obtained from the exergy and material flow analysis of the construction sector and compile only the most relevant conclusions presented in each chapter.

Energy intensity of the construction sector: This study details some of the main limitations of resource use related to the material and energy flows, providing possible quantifications. The results of this study conclude that CDW should be prioritized for reuse and recycling, especially energy-intensive materials, from an energy conservation perspective. It is suggested that the construction sector should focus on the increasing use of materials with higher recyclability; these materials could be recirculated in the system, which in turn will reduce the primary resource inputs in the economy.

Exergetic efficiency of construction material manufacturing: The results obtained from this analysis suggest that exergy resources are being used very inefficiently and theoretically a wide margin still exists to optimize present industrial processes. It may not always be economically or technically feasible to reduce significantly the process inefficiencies because of low cost energy and material resources. However, reducing exergy losses from manufacturing processes may become more and more attractive in the near future due to scarcity of finite non-renewable resources, regulatory limitations, and environmental concerns.

Exergetic life cycle analysis: The results demonstrate that manufacturing process is the most energy-intensive stage of a products' whole life cycle and also responsible for the major inefficiency compared to other life cycle stages such as extraction and recycling processes. Thus, improvement in manufacturing processes will facilitate to improve the overall resource sustainability of the construction sector through reducing exergy flows and associated waste and emissions during the products' life cycle. Besides, the material choice can also be discussed depending on the ELCA results since it is a straight-forward parameter that can easily be communicated.

5.3 Perspectives of future studies

This dissertation has opened the way for assessing the exergy resources of the construction sector and their degradation during the life cycle period. Obviously it is subject to further improvements and refinements in future studies, with the help of better statistics and process data. An efficient management of our resources should be based on global and reliable information sources. Hence, improved data bases, including global statistics on construction materials, the opening of global information channels, and interpretations of the information are urgently required. For that purpose, this thesis has identified the necessity of the following data to be compiled worldwide for all construction materials: (i) yearly production data which is currently available for only limited countries; (ii) detailed process data including both production and recycling; (iii) energy, water, and raw materials consumption; (iv) generation of CDW, their composition, and management route; and (v) material reserve in the nature and total stocks in buildings and infrastructure.

In many cases, the above mentioned information are hidden or eliminated by companies for their own economic benefits, CDW data for instance due to low market price. This cannot be forgotten that the earth and its resources are common good, and consequently the state of this planet should be of global knowledge.

This work has been based on many different information sources. The lack of data needed for the calculations, lead this thesis to make important assumptions which might have accuracy loss in the results. However, this is the first step in determining the resource use efficiency in the construction sector using exergy analysis and need to be updated for all materials used in this sector.

The main activity that has remained undone and crucial for an appropriate natural resource assessment is a deeper analysis in global scale, especially a comparison between developed and developing world. It is recognized that most of the studies concerning construction sector have been performed in the developed countries although rapid urbanization is observed in the least developed and developing countries. As a result, the state of the construction sector of these regions is completely unknown. Beside, construction is one of the most labour intensive sectors and thus extended exergy analysis would be useful in assessing the overall sustainability of this sector.

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Annex

Annex A: Renovation benefits in building energy consumption: An assessment.

This summarizes the results of a case study that has been done during the short research stay at SupAgro, France within the Ecotech Sudoe project. It highlights the energy savings potential that can be obtained through implementing intelligent techniques (intelligent low energy lighting and architectural sun screening solution), material selections (aluminium double glazing window frames and joinery, inside cork insulation), and improved solutions for heating and ventilation systems related to the renovation of building at SupAgro for tertiary activities (classrooms and offices). Real time energy consumption after renovation of the building has been compared with the building energy demand in Mediterranean region, using a simulation tool.

Appendices

Appendix A

Supporting information for

Hoque, M. R., X. Gabarrell Durany, C. Sendra Sala, G. Villalba Méndez, L. Talens Peiró, and T. Vicent Huguet. 2012. Energy intensity of the Catalan construction sector: An application of material and exergy flow analysis. *Journal of Industrial Ecology*, *16*(5): 699-709.

Appendix B

Supporting information for

Hoque, M. R., G. Villalba Méndez, X. Gabarrell Durany, and C. Sendra Sala. 2012. Exergetic efficiency analysis of construction material manufacturing. *To be submitted to Journal of Cleaner Production* (June 2013).

Appendix C

Supporting information for

Hoque, M. R., X. Gabarrell Durany, G. Villalba Méndez, and C. Sendra Sala. 2013. Exergetic life cycle assessment: An improved option to analyze resource use efficiency of the construction sector. In: *Sustainability in Energy and Building: Smart Innovation, Systems and Technologies*, Hakansson et al. ed., 22:313-321. Berlin, Heidelberg: Springer Berlin Heidelberg.

Resumen

Ésta tesis tiene como objetivo evaluar el consumo de recursos del sector de la construcción, los residuos y las emisiones generadas por el sector. Ésto está motivado por el hecho de que el sector de la construcción es responsable de una gran cantidad de consumo de recursos y representa casi el 9% el valor bruto añadido al producto interno bruto del mundo. La evaluación considera la perspectiva del ciclo de vida, desde la extracción de materias primas, a través de la construcción y fabricación de productos, materiales de transporte, la construcción, la generación de residuos de demolición, el transporte de residuos, el tratamiento y disposición final. El objetivo es identificar las oportunidades y mejorar los criterios de selección de materiales, el procesado, la reutilización y el reciclado para el uso sostenible de los recursos. Debido a la complejidad de los sistemas de edificios e infraestructuras, compuestas de muchos componentes que interactúan, siempre es difícil llevar a cabo una contabilidad de los recursos precisos dentro de éste sector. En esta perspectiva, el concepto de análisis de flujo de materiales y la evaluación del ciclo de vida (ACV), y el análisis de exergía se tratan como herramientas de contabilidad de recursos y se centra en sus aplicaciones en el sector de la construcción. Además del análisis sectorial, ésta tesis, también analiza la eficiencia de los procesos de fabricación y el ciclo de vida completo de los productos con base a exergía. Todos los procesos y los productos seleccionados son relevantes para el sector de la construcción, y éste análisis tiene como objetivo proporcionar conocimientos de despersonalización en el uso de materiales del sector.

En el capítulo 1, se expone el marco teórico en que los análisis de flujo de exergía y los materiales se utilizan en la evaluación del metabolismo de los recursos del sector de la construcción, que destacan la importancia de éste sector en términos de flujos de recursos y la generación de residuos y emisiones. Éste capítulo, también introduce la eficiencia exérgica y herramientas de evaluación del ciclo de vida exergéticos, que explica las limitaciones del análisis de la energía y el ACV, y cómo la aplicación de éstos métodos a base de exergía puede ofrecer mejores perspectivas sobre la eficiencia del uso de los recursos en los procesos de fabricación en toda la vida de los productos, respectivamente. La Ecología Industrial, se presenta al introducir el enfoque basado en los sistemas y el marco termodinámico en el que el sector de la construcción se analiza en este estudio.

El capítulo 2, presenta los resultados de los análisis de flujo de materiales y exergía del sector de la construcción catalana en el año 2001. En ese momento, Cataluña tenía un adicional de 52 millones de toneladas de existencias de materiales para el sector y generaba 7 millones de toneladas de residuos de construcción y demolición, de los cuales sólo el 6,5% son recicladas o regeneradas. El estudio muestra que la fase de fabricación consume la mayor parte de los recursos de energía durante el ciclo de vida del conjunto de los productos, seguidos de transporte de materiales, que representa el 57% y el 4% del consumo de exergía, respectivamente. Se señala que la mejora en la selección de materiales, tecnologías de fabricación y diseño para el desmontaje, conduce a la sostenibilidad del sector, para conseguir una mejora de la eficiencia del uso de recursos.

En el capítulo 3, se menciona el rendimiento exergético de los procesos de producción, tanto en el proceso de producción primaria como secundaria (reciclaje), de los materiales de construcción que se calcula, con el fin de evaluar la calidad de los materiales, las pérdidas de exergía, y el potencial de mejora de procesos. Ésto sirve para cuantificar el potencial de mejora de los procesos de fabricación actuales que abordan las deficiencias de fabricación de los nueve principales materiales de construcción no renovables: aluminio, acero, cobre, cemento, hormigón, cerámica, vidrio, polipropileno y cloruro de polivinilo. La Eficiencia Exergía basada en la segunda ley de la termodinámica es determinada con el fin de comparar la eficiencia exergía teórica y la eficiencia exergía del proceso real. La gran diferencia entre los requisitos teóricos y empíricos de exergía en los procesos de fabricación sugiere que las oportunidades para una mejor utilización de exergía industrial todavía existen, pero requieren un diseño y mejoras en la tecnología. Los resultados demuestran que los recursos se utilizan de manera más eficiente en los procesos de reciclaje, en comparación con los procesos de fabricación primaria.

En esta tesis se presenta una teoría (capítulo 4) para determinar como de eficientemente se utilizan los recursos en las aplicaciones de la construcción, utilizando la metodología de análisis del ciclo de vida exergético desde un enfoque universal. Esto incluye la extracción de materias primas, la fabricación de resina y de gestión de las etapas del ciclo de vida de los residuos al final de su vida. La irreversibilidad durante el ciclo de vida completo permite evaluar el grado de perfección termodinámica de los procesos de producción y llevar a cabo la evaluación de la cadena de producción entera. Ciclo de vida global de la eficiencia exérgica de polipropileno y cloruro de polivinilo se cuantifica en 27,1% y 9,3%, respectivamente, que se caracteriza por una baja eficiencia en la fabricación y los procesos de reciclaje para ambos materiales. Desde el punto de vista de la conservación de recursos, el reciclado mecánico se ha sugerido como la opción viable para la gestión de residuos de plástico al final de su vida, ya que los materiales de bucles vuelven a su ciclo de vida original y reduce las aportaciones de recursos primarios en la producción.

Annex A: Renovation benefits in building energy consumption: An assessment.

This annex A summarizes the results of a case study that has been done during my short research stay at SupAgro, France. It highlights the energy savings potentials that can be obtained through implementing intelligent techniques (intelligent low energy lighting and architectural sun screening solution), material selections (aluminium double glazing window frames and joinery, inside cork insulation), and improved solutions for heating and ventilation systems related to the renovation of building at SupAgro for tertiary activities (classrooms and offices). Real time energy consumption after renovation of the building has been compared with the building energy demand in Mediterranean region, using a simulation tool.

Analysis of buildings' energy consumption requires detailed interactions among the building, HVAC system, and surroundings (weather) as well as mathematical/physical models that are effective in characterizing each of those items (Fumo et al. 2010). Information on energy demand profile and energy consumption of buildings are used to assess the use of energy-efficient technologies in buildings by comparing conventional heating and cooling equipment with technologies such as cogeneration, tri-generation, ground-coupled heat exchangers, solar thermal and solar photovoltaic technologies, among others (Sakulpipatsin 2010).

Design of low-energy buildings addresses the target of reducing the operating energy. This can be done by means of several technologies including, improved insulation, better performing windows, and renewable energy production through solar photovoltaic panels. Besides, a reduced demand for operating energy can be achieved by using materials with optimum energy performance. Heating or cooling energy has to be supplied to maintain a certain comfort level. Additional power is needed to operate lighting, appliances and building service systems. Due to the increased awareness of energy consumption and related CO_2 emissions, building regulations such as the European Buildings Directive (Directive 2002/91/EC) in Europe, Minergie in Switzerland (Minergie Standards. 2008), or programs such as LEED (2007) in the USA have been established over the last years.

To evaluate the final energy efficiency in building, the influence of the following criteria need to be analyzed:

(i) Present technology and fuel used for electricity production and production efficiency;

(ii) HVAC in building system and their efficiency;

(iii) Heat pump efficiency in domestic or commercial hot water supply system for heating purpose; and

(iv) Role of material with higher and/ or lower heat transmissivity in increasing energy performance.

SupAgro case study

As part of Ecotech-Sudoe project, Montpellier Supagro has undertaken a pilot project to reduce the footprint of a building (figure A-1) through renovation for tertiary activities (office and class room), focusing on the carbon footprint and energy consumption.

Figure A-1: Renovated building at SupAgro.

The French thermal regulation RT 2005, which has been replaced by RT 2012, applies to both residential and tertiary buildings during planned renovations in order to improve energy performance including primary energy consumption and internal comfort temperature of the reference building.

Regulatory measures are different according to the importance of the work undertaken by the client:

1. For heavy renovations of buildings over 1000 m², completed after 1948, the regulations define an objective overall performance for the renovated building. These buildings should also be subject to a feasibility study of energy supply prior to filing the application for a building permit. This first part of the RT is applicable for building permits filed after March 31, 2008.

2. For all other cases of renovation, the regulations define the minimum performance for the item replaced or installed. This second part of the RT for contracts or specifications accepted from 1 November 2007.

Climate condition of the region

The climate of Montpellier is Mediterranean, situated in the climate zone H3 of RT 2005 with an altitude of 81 meters. The annual precipitation is about 800 mm. Montpellier is the least windy city in the Gulf of Lions with reliefs with 70 days per year of wind ≥ 57.6 km / h. Average temperature recorded between 1981 and 2010 are presented in table A-1

Table A-1: Average temperature in Montpellier between 1981 and 2010.

Month	01	02	03	04	05	06	07	08	09	10	11	12	Yearly average
Average minimum temperature (°C)	2.2	3.3	4.9	7.8	11.2	14.6	17.1	16.7	14.2	10.6	5.9	2.8	9.3
Average maximum temperature (°C)	11.1	12.4	14.7	17.5	21.1	25.3	28.4	27.7	24.7	20.2	14.7	11.7	19.1

Building description

The building has an ideal orientation for summer comfort and does not require sun screen except Southwest facade. As a result, the renovation plan includes architectural sun screening solution for the windows to improve summer comfort. It has the following insulations, which are not changed during the renovation:

- Exterior wall insulated with metal siding (U = 0.42 W / (m² K).)
- Roof is insulated bitumen (U = 0.41 W / (m² K).)
- Low concrete floor un-insulated grade (U = 0.5 W / (m² K).)
- Aluminum joinery double glazing without shading = 2.6 W / (m² K).
- Metal gate (U = 1.5 W / (m² K).).

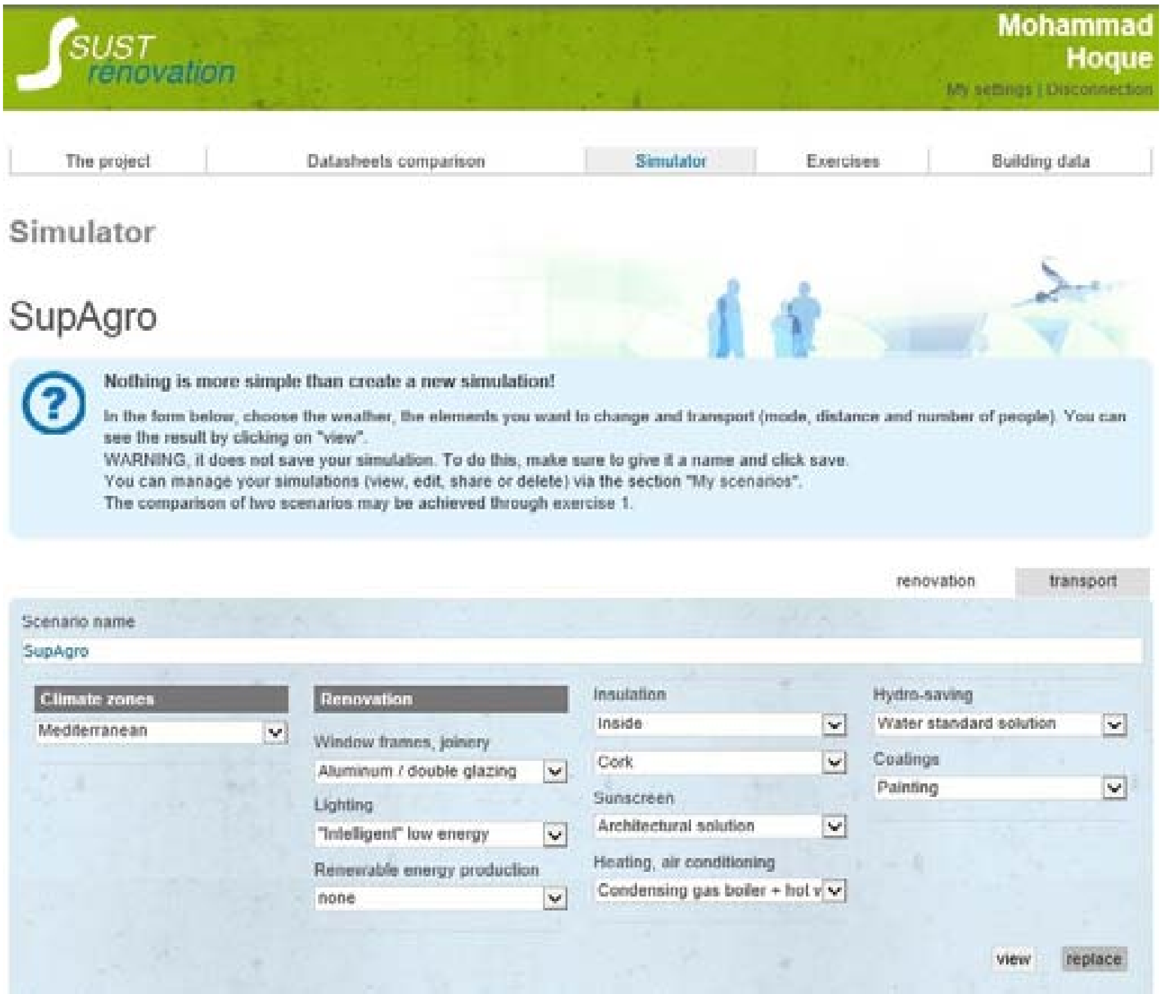
Space heating is provided by a central gas boiler through radiant heat. The air exchange in the area of the building is performed naturally and there was no air conditioning system before renovation.

This assessment aimed to analyse the primary energy consumption of the renovated building before and after renovation. However, due to data unavailability the assessment compares real time energy consumption after renovation with the standard energy demand. Figure A-2 and A-3 show the interior orientation of the case study building before and after renovation, respectively.

Figue A-2: Interior orientation of the building before renovation.

Figure A-3: Interior orientation of the case study building after renovation.

A simulation tool (SUST renovation) has been developed during the pilot project period in order to assess energy consumption, summer comfort, and LCA impacts associated with renovation and transport. This web-based simulation tool allows users to create their own scenarios, and it calculates the mentioned parameters based on the defined scenario (as presented in figure A-4).



Nothing is more simple than create a new simulation!

In the form below, choose the weather, the elements you want to change and transport (mode, distance and number of people). You can see the result by clicking on "view".
WARNING, it does not save your simulation. To do this, make sure to give it a name and click save.
You can manage your simulations (view, edit, share or delete) via the section "My scenarios".
The comparison of two scenarios may be achieved through exercise 1.

Scenario name: SupAgro

Climate zones: Mediterranean

Renovation

Window frames, joinery: Aluminum / double glazing

Lighting: "Intelligent" low energy

Renewable energy production: none

Insulation: Inside

Cork

Sunscreen: Architectural solution

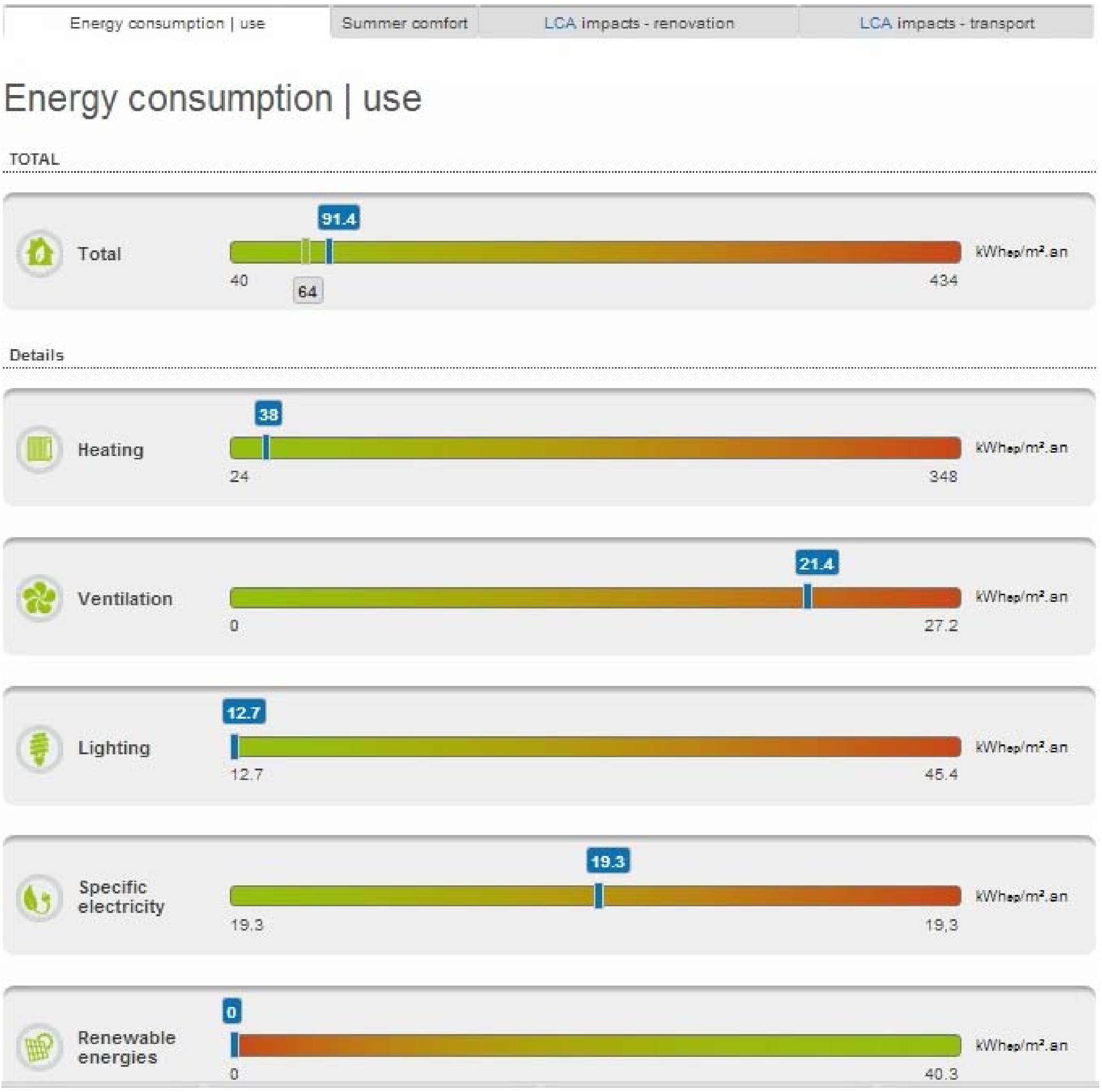
Heating, air conditioning: Condensing gas boiler + hot v

Hydro-saving: Water standard solution

Coatings: Painting

Figure A-4: Defining scenario in web-based SUST renovation simulation tool.

This figure demonstrates a scenario based on the renovation activities performed in the case study building. Based on this scenario, the simulation tool accounted the energy consumption during the use phase of the building after renovation (figure A-5).



Energy consumption | use
Summer comfort
LCA impacts - renovation
LCA impacts - transport

Energy consumption | use

TOTAL

Total
91.4
40
64
434
kWhep/m².an

Details

Heating
38
24
348
kWhep/m².an

Ventilation
21.4
0
27.2
kWhep/m².an

Lighting
12.7
12.7
45.4
kWhep/m².an

Specific electricity
19.3
19.3
19,3
kWhep/m².an

Renewable energies
0
0
40.3
kWhep/m².an

Appendix A: Supporting information for

Hoque, M. R., X. Gabarrell Durany, C. Sendra Sala, G. Villalba Méndez, L. Talens Peiró, and T. Vicent Huguet. 2012. Energy intensity of the Catalan construction sector: An application of material and exergy flow analysis. *Journal of Industrial Ecology*, 16 (5): 699-709.

Summary

This supplement contains descriptions of chemical exergy calculation, calculation of β values for wood products, exergy calculation of plastic products from β values and Group contribution, and additional information about the data used in the case study analyses.

Calculation of β for wood products: The exergy of wood and wood products was quantified by calculating the dependency of the ratio β = e^{o}_{ch} /C^{o}_{1} on the atomic ratios H/C, O/C and N/C, where C^{o}_{1} denotes the lower heating value (LHV). Beta (β) values for wood and wood products were calculated using the Szargut and Styryslka equations based on the compositional data of wood and the lower heating value (LHV). For wood with $Zo_2/Zc \leq 2.67$ (equation A.1).

$$\beta = \frac{1.0412 + 0.2160 \cdot (Z_{H_2}/Z_C) - 0.2499 \cdot (Z_{O_2}/Z_c) \cdot [1 + 0.7884 (Z_{H_2}/Z_C)] + 0.0450 (Z_{N_2}/Z_C)}{1 - 0.3035 \cdot (Z_{O_2}/Z_C)} \qquad \text{(A.1)}$$

where Z_{H_2}, Z_C, Z_{O_2}, and Z_{N_2} are the mole fractions of hydrogen, carbon, oxygen and nitrogen, respectively.

Table A.1: Exergy calculation of plywood using elemental composition and LHV.

Elemental composition	%
C	48.10
H	5.87
O	42.50
N	1.45
Ash	2.10
Total	100.02
$Zo_2/Zc \leq 2,67$	0.88358
Beta (β)	1.1299
LHV (MJ/Kg)	17.679
Exergy (MJ/Kg)	19.9747

Exergy calculation of plastics from β value and group contribution: To calculate the β values of oxygen-containing hydrocarbons where the ratio of oxygen to carbon is O/C ≤ 0.5 and for solid hydrocarbons equations A.2 and A.3 were used. The elemental composition of hydrocarbons is taken from ECN.

$$\beta = (1.0438 + 0.0158(H/C) + 0.0813(O/C)) \quad (A.2)$$

$$\beta = 1.0435 + 0.0159(H/C) \quad (A.3)$$

An example of the calculation of the chemical exergy from organic groups' exergy, the method proposed by Szargut and colleagues (1988) for butadiene in acrylonitrile butadiene styrene (ABS) is summarized in table A.2.

Table A.2: Chemical exergy calculation of butadiene.

Compound	Group	Number of group	Chemical exergy (kJ/mole)	Total exergy (kJ/mole)
Butadiene, CH_2=CH-CH=CH_2, molar mass 54.092	CH_2=	2	675.68	1351.36
	-CH=	2	559.95	1139.9
	Exergy, Butadiene (MJ/Kg)			46.056

Table A3. Construction types for estimating material and energy inputs.

Building	Infrastructure
Residential buildings	Road and railways
Hospitals and institutional cares	Harbors and airports
Offices, industries, and warehouses	Waterworks and sewerage networks
School, Universities, and research centers	Landslide / flood control
Trade centers, hotels, and catering enterprises	Electrical grids/ gas and petroleum pipelines/ telecommunications
Cultural and sports centers, and others	Dams
Renovation of building facilities	Parks and others
	Maintenance of infrastructure networks

Table A.4: Material use in the construction sector.

Material category	Origin/ PRODCOM code	Name of Mineral/ Material
Minerals	Domestic extraction (DE)	Clay
	DE	Sand and gravel
	DE	Silica and silicioud sand
	DE	Limestone ornamental
	DE	Limestone other uses
	DE	Creta (chalk)
	DE	Dolomite
	DE	Granite ornamental
	DE	Granite (other uses)
	DE	Sandstone ornamental
	DE	Sandstone (other uses)
	DE	Basalt
	DE	Marga (Marl)
	DE	Porphyry
	DE	Serpentine
	DE	Marble ornamental
	DE	Marble (other uses)
	DE	Slate other uses
	DE	Gypsum

Minerals	14111290	Porphyry, basalt and other monumental/building stone, crude, roughly trimmed/merely cut (excl. calcareous monumental/ building stone of gravity>2.5kg/$10m^3$ granite and sandstone)
	14122050	Calcined and sintered dolomite; crude; roughly trimmed or merely cut into rectangular or square blocks or slabs
	14122050	Calcined and sintered dolomite; crude; roughly trimmed or merely cut into rectangular or square blocks or slabs
	14122070	Agglomerated dolomite (incl. tarred dolomite)
	14502340	Asbestos
	14502363	Feldspar and other feldspathic materials
	26701240	Other calcareous stone, nes, cut/sawn, flat/even surface, otherwise worked
	26701260	Worked monumental or building stone and articles thereof,of granite excl. tiles,cubes and similar articles,largest surface area is < $7cm^2$, setts, kerbstones and flagstones
	26701280	Worked monumental or building stone and articles thereof (excl. of calcareous stone; granite or slate, tiles; cubes and similar articles; the largest surface area is < 7 cm^2)
	26701100	Worked monumental/building stone and articles thereof,in marble,travertine and alabaster excl. tiles, cubes/similar articles, largest surface <$7cm^2$,setts,kerbstones,flagstones
Natural rocks and industrial	26701210	Natural stone setts; kerbstones and flagstones (excl. of slate)
	26701230	Tiles, cubes, ..., artificially colored granules, ..., for mosaics

minerals	26701290	Worked slate and articles of slate or of agglomerated slate
	26821690	Articles of stone or other mineral substances, n.e.c.
	26821630	Mixtures and articles of heat/sound-insulating materials n.e.c.
Ceramics	2622	Manufacture of sanitary ceramic
	2623	Manufacture of insulators and insulating parts of ceramic material
	2630	Manufacture of ceramic tiles
	2640	Manufacture of bricks, tiles and clay products for construction
Cement, Concrete and derivatives	2651	Manufacture of cement
	2652	Manufacture of lime
	2653	Gypsum, Plaster and derivatives
	2663	Mortars, concrete, and derivatives
Asphalt and bituminous mixtures	26821300	Bituminous mixtures based on natural and artificial aggregate and bitumen or natural asphalt as a binder
Wood and wood products	2010	Manufactured articles from wood and cork, except furniture
	20101010 and 3200	Railway or tramway sleepers (cross-ties) of wood
	20101033 - 3115	Wood, plans, polished or sawn
	20104005	Sawdust
	20104009	Wood waste and scrap (incl. agglomerated in logs; briquettes; pellets or similar forms) (excl. sawdust)
	20201103 -1259	Plywood
	20201333-1350	Particle board

	20201413-1475	Fiberboard
	20202113 and 2118	Sheets (Veneer sheets, sheets for plywood, Coniferous and tropical wood veneer sheets)
	20202200	Densified wood; in blocks; plates; strips or profile shapes
	20301110	Windows; French-windows and their frames of wood
	20301150	Doors and their frames and thresholds of wood
	20301215 and 1219	Parquet panels of wood
	20301230	Shuttering of wood for concrete constructional work
	20301250	Shingles and shakes of wood
	20301300	Other wood for builders' joinery and carpentry
	20302000	Prefabricated buildings of wood
Paint and chemical products	24301150-1290	Paints and varnishes
	24302220	Prepared driers
	24302230	Stamping foils
	24302245	Pigments, dispersed (a non-aqueous media), liquid/ paste form, used in paints/ enamels manufacture; dyes and other color matter p.r.s. incl. metallic powders/ flakes excl. pearl essence
	24302253	Glaziers' putty, grafting putty, resin cements, caulking compounds and other mastics
	24302260	Non-refractory surfacing preparations, and organic composite solvents and thinners
	24302273-2279	Organic solvents or thinners
	24621013, 1015 and	Glues

	1095	
	24664867	Fire-proofing; water-proofing and similar protective preparations used in the building industry
Plastics	25212130-2270	Rigid pipes and plastic fittings
	25231155, 1159 and 1190	Floor coverings
	25231250, 1270 and 1290	Plastic baths; shower-baths and wash-basins, lavatory pans and similar sanitary ware
	25231300	Plastic reservoirs; tanks; vats; intermediate bulk and similar containers; of a capacity > 300 liters
Plastics	25231450	Plastic doors; windows and their frames and thresholds for doors
	25231470	Plastic shutters; blinds and similar articles and parts thereof
	25231550	Builder's fittings and mountings intended for permanent installation of plastics
	25231590	Other articles of plastic for construction incl. raw plugs and other wall plugs; trunking, ducting and cable trays for electrical circuits
	25232000	Prefabricated buildings, of plastics
	25242400	Plastic parts for lamps; lighting fittings and illuminated signs and name-plates
Glass	2611	Manufacture of flat glass
	2612	Manipulated and transformed flat glass
	2614	Articles fiberglass
	26151200	Paving blocks. of glass, for building or construction purposes, n.e.c.
Metals	28111030	Prefabricated buildings of iron or steel

	28111050	Prefabricated buildings, of aluminum
	28112100	Iron or steel bridges and bridge-sections
	28112200	Iron or steel towers and lattice masts
Metals	28112310	Iron/ steel equipment for scaffolding, shuttering, propping/ pit-propping incl. pit head frames and superstructures, extensible coffering beams, tubular scaffolding and similar equipment
	288112330-60	Building structures of iron or steel sheets
	28112370	Aluminum structure and parts of structures., n.e.c.
	2812	Manufacture of metallic closures
	28121030	Iron or steel doors, thresholds for doors, windows and their frames
	28121050	Aluminum doors, thresholds for doors, windows & frames
	282212 and 13	Manufacture of boilers and radiators for central heating
	2863	Manufacture of locks and fittings
	2874	Manufacture of bolts, screws, chains and springs
	28751110	Stainless steel sinks and wash basins
	28752737	Iron or steel non-mechanical ventilators, guttering, hooks and similar articles used in the building industry (excl. forged or stamped)
	28752741	Perforated buckets and similar articles of iron or steel sheet used to filter water at the entrance to drains
Electric and lighting products Electric	3130	Manufacture of electrical wires and cables
	3150	Manufacture of electric lamps and lighting devices

Table A.5: Material, trade, and transport data sources.

Category of data	Source
Mineral extraction	Annual mining statistics of Spain 2001, Ministry of Industry, Tourism and Trade (Estadística minera. 2001).
Cement production	Draft reference document on the best available techniques in the cement, lime and magnesium oxide manufacturing industries published by the European Commission (IPPC 2010)
Production of Cement derivatives, glass, ceramics, plastics and bitumen refinery	Ecoinvent v2.0 database for European average (Ecoinvent 2007); Catalan and Spanish industry data (IDESCAT 2001; INE 2010)
Biomass	Forestry statistics published by the Department of Agriculture, Food and Rural Action of the Generalitat de Catalunya (GENCAT 2009)
Industrial production, foreign trade	Statistical Yearbook 2001 published by Statistical Institute of Catalonia (IDESCAT, 2009)
Freight transport	Permanent survey of road freight transport, Spain 2001 (Ministerio de Fomento, 2001)
Foreign trade	Official statistics of Catalonia, foreign sector. (IDESCAT 2009)
Construction and demolition waste	II National Plan of Construction and Demolition Waste (II PNRCD)

Table A.6: Exergy calculation data sources of minerals and manufactured products.

Data	Source
Chemical species and minerals	Szargut et al. 1988, Meester et al. 2006, Dewulf et al. 2007, Finnveden and Ostlund 1996, Valero Delgado 2008, Talens Peiró et al. 2010)
Manufacturing of plastic products, bitumen refinery	EcoInvent v2.0 database for European average (Ecoinvent 2007)
Manufacturing of metallic products	Ayres and Ayres. 1999, Costa et al. 2001, Masini et al. 2001, Szargut et al. 1988
Bituminous mix products	Federici et al. 2008
Manufacturing of cement and cement derivatives, glass, and ceramics	Reference document on best available techniques published by European Commission Joint Research Centre (EIPPCB 2009) , EcoInvent v2.0 data base (Ecoinvent 2007), Schmitz et al. 2011, Ciment Catala 2009.
LHV, wood composition and wood products	Energy research Centre of the Netherlands (ECN 2009), Szargut et al. 1988
Energy use for mineral extraction	Catalan industry data (IDESCAT 2009)

Table A.7: Composition and quantity of CDW generated in Catalonia in 2001.

Types of waste material	Weight percentage (%)	Quantity generated (1000 tonne)
Masonry (brick, tile or ceramic)	54.0	3698.7
Concrete	12.0	822.0
Stone	5.0	342.5
Sand, gravel and other aggregate	4.0	274.0
Wood	4.0	274.0
Glass	1.5	102.7
Plastic	1.5	102.7
Metal	2.5	171.2
Asphalt	5.0	342.5
Gypsum	0.2	137.0
Paper	0.2	137.0
Rubbish	7.0	479.5
Others	3.1	212.3

Data source: PNRCD 2001.

Table A.8: Standard chemical exergy of construction minerals.

Mineral name	Formula/ Composition/ input raw materials	Chemical exergy (MJ/Kg)	Source/ Reference
Clay	Mixture of minerals	0.108	Dewulf et al. 2007
Shale	Mixture of minerals	0.082	Dewulf et al. 2007
Sand and gravel	SiO_2	0.090	Dewulf et al. 2007
Silica and Siliceous sand	SiO_2	0.031	Dewulf et al. 2007
Limestone/ Chalk	$CaCO_3$	0.186	Dewulf et al. 2007
Dolomite	$CaMg(CO3)_2$	0.126	Dewulf et al. 2007
Granite	Mixture of minerals	0.090	Dewulf et al. 2007
Basalt	Mixture of minerals	0.031	Dewulf et al. 2007
Marl/ Lime	CaO	0.090	Composition estimated
Porphyry	Variety of igneous rock	0.743	Composition estimated
Serpentine	$(Mg,Fe)_3Si_2O_5(OH)_4$	0.187	Valero Delgado 2008
Marble	-	0.090	Gasparatos et al. 2008
Slate/ Graphite	Metamorphous rock	34.200	Dewulf et al. 2007
Gypsum	$CaSO_4.2H_2O$	0.150	Dewulf et al. 2007
Feldspar	$KAlSi_3O_8$	0.067	Dewulf et al. 2007
Borax	$Na_2[B_4O_5(OH)_4]\cdot 8H_2O$	0.235	Dewulf et al. 2007
Barite	$BaSO_4$	0.128	Dewulf et al. 2007
Sandstone	SiO_2	0.032	Gasparatos et al. 2008
Kaolin	$Al_2Si_2O_5(OH)_4$	0.057	Dewulf et al. 2007

Table A.9: Standard chemical exergy of fabricated construction materials made from minerals

Material name	Formula/ Composition	Chemical exergy (MJ/Kg)	Comment/ Source
Paving slab	Natural stone	0.192	Composition estimated
Rock wool	Produced industrially from quarried basalts.	0.337	Composition estimated from Marabini and colleagues (1998)
Ceramic brick	SiO_2-57.9%, Al_2O_3-20.4%, CaO- 5.95%, MgO-3.84%, Na_2O-1.17%, Fe_2O_3-5.25%, TiO_2-0.68%, K_2O-2.0%, SO_3-2.01%	0.827	Calculated based on the composition of clay brick as specified in Cevik and colleagues (2011)
Ceramic tile	SiO_2-67.76%, Al2O3-17.89%, CaO-0.74%, MgO-1.06%, Na_2O-0.71%, Fe_2O_3-5.16%, TiO_2-0.96%, K_2O-5.48%, ZnO-0.55%	0.724	Composition estimated from IPPC (2007)
Sanitary ceramic	SiO_2-62.8%, Al_2O_3-33%, CaO-1.77%, MgO-0.17%, Na_2O-0.022%, Fe_2O_3-0.5%, TiO_2-0.338%, K_2O-1.2%, ZnO-0.20%	0.798	Composition estimated from IPPC (2007)
Clinker	Mixture of C_2S, C_3S, C_3A, C_4AF	0.87	Calculated based on the composition of clinker
Cement	Unspecified	0.532	Estimated based on the types of cement commonly used in Catalonia
Concrete	86% Sand and gravel, 13.2% Cement, 0.8% recycled residue	0.139	Adopted from Ecoinvent (2007)
Gypsum panel	89.6% $CaSO_4 \cdot 2H_2O$, 10% waste paper or wood, 0.3% residue	1.35	Adopted from IPPC (2010)
Concrete	86% Sand and gravel, 13.2% Cement, 0.8% recycled residue	0.139	Adopted from sustainability software GABI
Mortar	80% Sand and gravel, 20% cement	0.179	Composition adopted from Ecoinvent (2007)
Flat glass	47.65% Siliceous sand, 32.97% Limestone, 18.88% Na_2CO_3	0.975	Estimated using flat glass composition
Glass fiber	25.8% Siliceous sand, 24.48% Limestone, 32.36% Clay, 13.11% Boric acid, 1.97%	0.833	Estimated using glass fiber composition

Table A.10: Standard chemical exergy of wood, plastic, metal, and organic products

Product name	Formula/ Composition	Chemical exergy (MJ/Kg)
Plywood	48.1% C, 5.87% H, 42.5% O and 1.45% N	19.975
Waste wood	50.7% C, 5.91% H, 40.1% O and 1.68% N	17.939
Particle board	51.8% C, 5.81% H, 38.8% O and 2.96% N	20.238
Hard board	48% C, 6.05% H, 42.3% O and 0.49% N	20.181
Soft board	48.8% C, 6.02% H, 42.6% O and 0.34% N	20.054
Sawdust	% (C, H, O, N) = 49.3, 5.93, 43.3, 0.4	20.432
Railroad sleeper	% (C, H, O, N) = 52, 6.03, 39.9, 0.38	19.445
Shuttering wood	% (C, H, O, N) = 45.5, 5.51, 37.8, 1.79	19.604
Wood door	% (C, H, O, N) = 48.1, 5.93, 42.6, 0.47	20.212
Laminated wood, Plywood	% (C, H, O, N) = 49.5, 6.16, 42, 0.58	18.185
High density polyethylene (HDPE)	$(-CH_2 - CH_2 -)n$	41.869
Low density polyethylene (LDPE)	$(-CH_2 - CH_2 -)n$	44.878
Polystyrene	$(-C_8H_8 -)n$	44.673
Polypropylene	$(- C_3H_6 -)n$	46.197
PVC (Polyvinyl chloride)	$(-C_2H_3Cl-)n$	19.324
ABS (Acrylonitrile, Butadiene, Styrene)	C_2H_3N, C_4H_6, C_8H_8	41.686
Nylon 6	$(-C_6H_{11}ON-)n$	32.982
Lubricating oil	Unspecified	42.141
Iron and Steel	Unspecified	6.750
Aluminum	Al	32.805

β value calculated based on the elemental composition of wood and plastics obtained from ECN (2009); Chemical exergy of Nylon 6 is calculated based on the group exergy contribution as suggested by Szargut and colleagues (1988); Composition of lubricating oil adopted from Espada and colleagues (2009) and standard chemical exergy calculated through group contribution; Standard chemical exergy of steel and aluminum is adopted from Ayres and Ayres (1999).

Exergy consumption in steel production: While calculating exergy consumption in steel production, material and energy inputs were taken into consideration. A detailed breakdown of material and energy consumptions have been presented in table A.11 and the results show that steel production using scrap as raw material or scrap recycling in electric arc furnace consume much less exergy in whole production chain.

Table A.11: Exergy consumption (material and energy) in primary steel production, steel production using scrap as raw material and steel scrap recycling to produce 1 tonne of steel.

Material/ energy	Exergy consumption in primary steel production (GJ)	Exergy consumption in steel production using 48% scrap (GJ)	Exergy consumption in scrap recycling in electric arc furnace (GJ)
Iron ore	1.412	0.695	-
Coking coal	27.747	13.648	-
Limestone	0.039	0.029	-
Fluorspar	0.116	0.116	-
Steel scrap	-	4.073	7.66
Air	0.359	0.195	0.025
Utility	8.298	5.157	8.6
Total	37.971	23.913	16.29

Data source: Ayres, and Ayres 1999; Masini et al. 2001; Michaelis et al. 1998

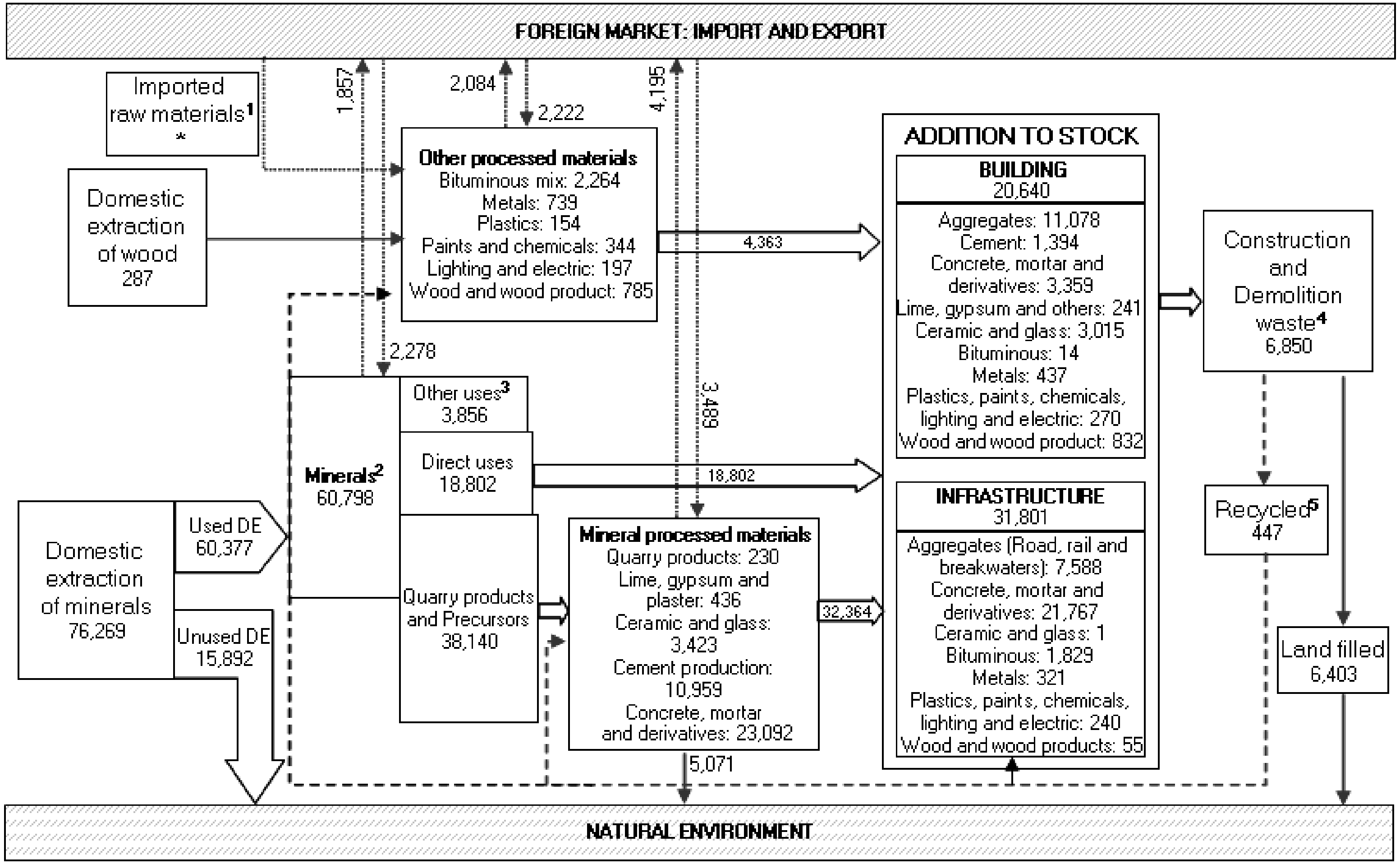


Figure A.1: Mass balance flow diagram of construction materials for Catalonia (in kilotonnes) in 2001. Asterisks denote unknown quantity.

[1] Data not available for construction material manufacturing because of commercial confidentiality except wood extraction from the region; [2] Non-metallic, non-energy minerals; [3] Minerals used in other industrial activities; [4] Data from Agencia Residus de Catalunya (Catalan Waste Agency) for 2001; [5] Data from Agencia Residus de Catalunya for 2001. Composition of recycled materials was estimated from Maña i Reixach et al. 2000, PNRCD 2001, and Río Merino et al. 2009.

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Appendix B. Supporting information for

Hoque, M. R., G. Villalba Méndez, X. Gabarrell Durany, and C. Sendra Sala. 2013. Exergetic efficiency analysis of construction material manufacturing. *Submitted to International Journal of Exergy* (June 2013).

Summary

This supplement contains descriptions of chemical exergy calculation, exergy efficiency of construction material manufacturing (both primary and secondary), and additional information about the data used in the case study analyses.

B.1. Calculation of chemical exergy

The chemical exergy of a compound depends on its composition and is calculated based on Gibbs free energy of formation and the exergy of the chemical elements in the substance equation (B.1). If the material is considered to be a mixture, then the chemical exergy of the mixture is calculated by summing the exergy of the mole fractions, as illustrated by equation (B.2) (Finnveden and Ostlund 1997; Szargut et al. 1998). The chemical exergy of a mixture containing *n* pure chemical species at the environmental state (T_0, P_0) is calculated by equation (B.3).

$$e^0_{ch,i} = \Delta_f G^o_i + \sum_{el} n_{el} e^0_{ch,el} \qquad (B.1)$$

$$E_{ch} = \sum_{i} n_i e^0_{ch,i} \qquad (B.2)$$

$$e_{ch} = \sum_{i} n_i e^0_{ch,i} + RT_0 \sum_{i} n_i \sum_{i} X_i \ln X_i \qquad (B.3)$$

where, $\Delta^f G^o_i$ is the standard Gibbs free energy of formation of the substance *i*; n_i is the number of moles of substance *i*; e^0_{ch} is the standard partial molar exergy; $e^0_{ch,i}$ is the partial molar chemical exergy of substance *i*; e_l is the elements in substance *i*; and E_{ch} is the chemical exergy of the substance; R the ideal gas constant (8.3149 J/mol.K), T_o the absolute reference temperature (298.15 K), and X_i the molar fraction of species *i* in the material. The first term in equation (B.3) is the contribution to the exergy content made by each fraction of the pure compounds, while the second term accounts for exergy variations caused by mixing of different species, assuming an ideal solution. Table (B.1) summarizes the exergy calculation of flat glass from its chemical composition.

Table B.1: Exergy calculation of flat glass from chemical composition. Composition adopted from IPPC (2010).

Name of species	Chemical formula	Weight %	Molar mass (g/mol)	n_i (mol/kg)	E_{ch} (MJ/Kg)	E_x (MJ)	X ln X	$RT_0 \sum n_i \sum X_i \ln X_i$ (MJ/kg)	Exergy of material (MJ/kg)
Silica	SiO_2	72.60	60.09	12.08	0.1315	0.095	-0.2413		
Aluminum oxide	Al_2O_3	0.70	101.96	0.07	1.9655	0.014	-0.0223		
Lime	CaO	8.60	56.08	1.53	1.9652	0.169	-0.2174		
Magnesium oxide	MgO	4.10	40.30	1.02	1.6574	0.068	-0.1688		
Sodium oxide	Na_2O	13.60	61.98	2.19	4.7790	0.650	-0.2647		
Potassium oxide	K_2O	0.30	94.20	0.03	4.3855	0.013	-0.0118		
Sulfur trioxide	SO_3	0.17	80.06	0.02	3.1113	0.005	-0.0084		
Total		100.07		16.95		1.015	-0.9346	-0.0393	0.975

Table B.2: Theoretical exergy required to produce 1kg of aluminum from alumina. Adopted from Choate and Green (2003).

Reactants, temp.	Products, temp	Reaction thermodynamics at 25°C						(Products-reactants) kJ/mol	C_p (J/mol.K), Al	Latent heat of fusion (kJ/kg), Al
Theoretical minimum energy for Hall-Heroult process based on gibbs free energy and enthalpy change									24.4	321
		Parameter	$2Al_2O_3+$	$3C =$	$4Al +$	$3\ CO_2$	Energy change (kJ)			
$2Al_2O_3$, 25°C	4 Al, 960 °C	ΔG (kJ/mol)	-3,164.6	0.0	0.0	-1,183.1	1,981.5	495.4		
3C, 25°C	$3CO_2$, 25 °C	ΔH (kJ/mol)	-3,351.4	0.0	0.0	-1,180.5	2,170.9	542.7		
		ΔS (J/mol.K)	101.8	17.1	113.2	640.8	635.1	158.8		
								kJ/kg of Al		
		Electrolytic work requirement (ΔG)						18359.32		
		Thermal energy for temperature maintenance (ΔH–ΔG)						1755.00		
		Thermal energy for Al at 960°C						845.54		
		Latent heat of fusion						321.00		
		Theoretical minimum						*21280.86*		

Table B.3: Standard chemical exergy of major inorganic and organic materials studied in the case study analysis.

Material name	Formula/ Composition	Chemical exergy (MJ/kg)	Source/ Comment
Ceramic	SiO_2-67.76%, Al_2O_3-17.89%, CaO-0.74%, MgO-1.06%, Na_2O-0.71%, Fe_2O_3-5.16%, TiO_2-0.96%, K_2O-5.48%, ZnO-0.55%	0.72	Calculated based on the composition of ceramic tile (IPPC 2007)
Clinker	C_2S 20%, C_3S 62%, C_3A 7%, C_4AF 9%, CaO 0.5%, MgO 1%	0.98	Clinker composition adopted from (IPPC 2010)
Cement	Clinker 95% and Gypsum 5%	0.93	Composition adopted from (IPPC 2010)
Concrete	Sand and gravel 86%, Cement 13.2%, recycled residue 0.8%	0.21	Composition estimated from Ecoinvent (2009) and IPPC (2010)
Flat glass	Siliceous sand 47.65%, Limestone 32.97%, Na_2CO_3 18.88%	0.98	Flat glass composition adopted from IPPC (2010a)
Polypropylene (PP)	C-85.6%, H-14.4%	46.31	Elemental composition of PP taken from ECN (2009)
Polyvinyl chloride (PVC)	C-38%, H-5%, Cl-56%	19.66	Elemental composition of PVC taken from ECN (2009)
Iron and steel	Fe-99.9%, Traces (P, S, Mn, C, O) 0.1%	6.76	Composition adopted from Ayres and Ayres (1999)
Aluminum	Al-99.3%, Fe-0.25%, Ti-0.2%, Si-0.2%, Traces (Cu, Mg, Mn, V, Zn)-0.05%	32.81	Composition estimated from Ayres and Ayres (1999)
Copper	Cu-100%	2.11	Composition adopted from Ayres and Ayres (1999)
Coking coal	C-62.25%, H-4.13%, O-10.62%, N-1.02%, S-1.13%, Ash/LOI-20.85%	26.62	Composition adopted from Vassilev and Vassileva (2009)
Petroleum coke	C-89.93%, H-3.71%, O-1.3%, N-1.1%, S-3.36%, Ash/LOI-0.25%	35.51	Composition adopted from Agrafiotis and Tsoutsos (2001)

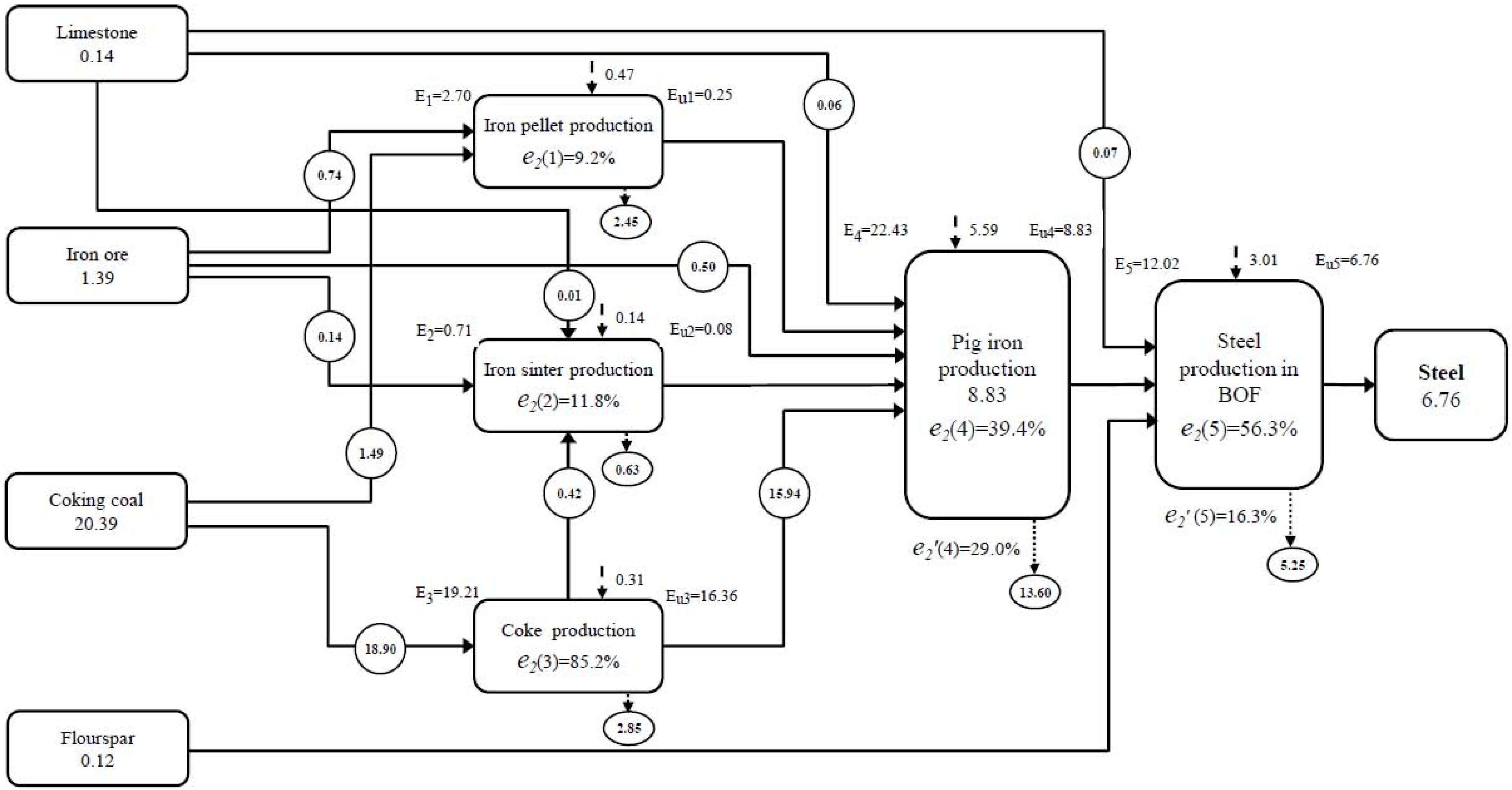

Figure B.1. Exergy efficiency of steel production: exergy flows in the production of 1 kg of steel; efficiency of different process steps and overall process. All numbers are in megajoules (MJ) unless otherwise specified.

Table B.4: Process exergy required for the case study materials

Process	Category of data	Data used in this analysis (MJ/kg)	Data source	Literature data (MJ/kg)	Reference
PP resin manufacturing	Calculation based on processes in Europe and Japan	37.25	Ayres and Ayres 1999; Narita et al. 2002; Ren et al. 2006	24.78-48.99	Dewulf and Van Langenhove 2004; EcoInvent 2009; Shutov 1999
PP recycling process	European average	13.40	Dewulf and Van Langenhove 2004	-	
PVC resin manufacturing	Calculation based on processes in Europe and Japan	44.00	Ayres and Ayres 1999; Narita et al. 2002	30.05-59.34	Dewulf and Van Langenhove 2004; EcoInvent 2009; Shutov 1999
PVC recycling process	European average	13.40	Dewulf and Van Langenhove 2004	-	
Primary steel production	Calculation based on US integrated iron and steel production using coal and iron ore.	27.00	Ayres and Ayres 1999	16.20-31.18	Ayres and Ayres 1999; Das and Kandpal 1997; Grimes et al. 2008; Sakamoto et al. 2999
Steel recycling	European average	11.70	Grimes et al. 2008	9.40-14.40	Das and Kandpal 1997; Grimes et al.2008; Sakamoto et al.1999
Primary aluminum production	Calculation based on US and Greek aluminum production process from Bauxite ore	127.42	Ayres and Ayres 1999; Balomenos et al. 2011	120.00-218.44	Ayres and Ayres 1999; Balomenos et al. 2011; Choate and Green 2003; Norgate et al. 2007
Aluminum recycling	European average	5.14	Grimes et al. 2008	5.14-10.92	Grimes et al. 2008; Norgate et al. 2007
Primary copper production	Based on literature data	71.34	Ayres and Ayres 1999; Masini and Ayres 1996	33.00-71.34	Ayres et al. 2006; Ayres and Ayres 1999; Grimes et al. 2008
Copper recycling	European average	6.30	Grimes et al. 2008	6.30-25.50	Grimes et al. 2008
Glass production	Calculation based on European average	8.37	EcoInvent 2009; IPPC 2010a	6.94-31.34	Ayres and Ayres 1999; CPIV 2011; IPPC 2010a
Glass recycling	Calculation based on European average	6.36	IPPC 2010a	5.99-8.02	IPPC 2010a; Schmidt 2005

Continuation of table B.4

Ceramic tile production	Based on European industry data	7.32	Agrafiotis and Tsoutsos 2001; EcoInvent 2009; IPPC 2007	5.45-11.78	IPPC 2007
Clinker production	Based on Catalan (Spain) cement industry data	3.07	Josa et al. 2007	3.07-7.07	IPC 2010; Josa et al. 2007
Ceramic recycling (to aggregate)	Calculation based on construction waste management practices in Catalonia (Spain)	0.04	Personal communication	-	
Cement grinding	Based on Catalan (Spain) cement industry data	0.29	Josa et al. 2007	0.29-0.54	IPC 2010; Josa et al. 2007
Cement production	Based on Catalan (Spain) cement industry data	3.56	Huntzinger and Eatmon 2009; IPPC 2010; Josa et al. 2007	3.56-8.01	Huntzinger and Eatmon 2009; IPPC 2010; Josa et al. 2007
Concrete production (only mixing process)	Based on industry data, European average	0.04	EcoInvent 2009	-	
Concrete recycling (Crushing to aggregate)	Calculation based on construction waste management practices in Catalonia (Spain)	0.04	Personal communication	-	

Table A.5: Exergy efficiency of secondary aluminum production.

Material/Utility	Process 1 (energy input 5.14 MJ/kg)		Process 2 (energy input 10.92 MJ/kg)	
	Input exergy (MJ)	Output exergy (MJ)	Input exergy (MJ)	Output exergy (MJ)
Aluminum scrap	32.74		32.74	
Energy	5.144		10.92	
Aluminum		31.28		31.28
Exergy efficiency (%)	82.6		71.4	

Table A.6 Exergy inputs and outputs in different steps for the production of 1 kg primary aluminum.

Process step	Process 1 (total energy input 218.4 MJ/kg)			Process 2 (total energy input 120.0 MJ/kg)		
	Input exergy (MJ)	Output exergy (MJ)	Exergy efficiency (%)	Input exergy (MJ)	Output exergy (MJ)	Exergy efficiency (%)
NaOH production	2.38	0.18	7.7	1.33	0.18	13.8
H_2SO_4 production	1.10	0.20	18.0	0.95	0.20	20.9
HF production	0.61	0.18	28.8	0.43	0.18	40.7
Bayer process	63.16	3.92	6.2	36.63	3.92	10.7
Synthetic cryolite production	1.02	0.47	46.2	0.61	0.47	77.2
AlF3 production	1.36	0.76	55.5	0.82	0.76	92.1
Anode baking	23.38	17.42	74.5	18.86	17.42	92.4
Hall–Héroult process	149.44	32.81	22.0	84.38	32.81	38.9
Overall process exergy efficiency (%)		*6.3*			*11.4*	

Table A.7 Exergy efficiency of construction materials: primary and secondary production processes, identifying improvement potentials.

Material	Exergy efficiency of the primary production process (%)		Exergy efficiency of the secondary production process (%)		Improvement potential (%)		
	Industrial practice[a]	Theoretical[b]	Industrial practice[c]	Theoretical[d],	Primary-Secondary (c-a)	Primary-Primary theoretical (b-a)	Secondary-Secondary theoretical (d-c)
Steel	16.3	56.3	35.6	81.6	19.2	40.0	46.0
Aluminum	10.7	22.7	82.3	92.1	71.6	12.0	9.8
Copper	1.8	50.9	22.9	70.7	21.0	49.0	47.9
Cement	12.6	34.1	-	-	-	21.5	-
Concrete	9.5	26.9	67.8	75.9	58.3	17.4	8.1
Ceramic	4.7	39.4	25.0	26.1	20.3	34.8	1.1
Glass	11.4	36.7	14.2	35.7	2.8	25.3	21.5
PVC	23.7	52.3	54.3	90.6	30.6	28.6	36.4
PP	54.6	60.8	70.4	90.3	15.8	6.1	19.9

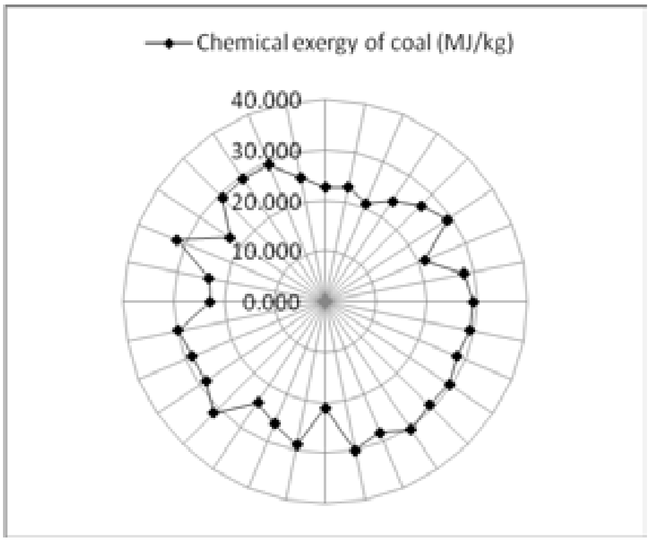

Figure B.2: Variation in chemical exergy of coal with different compositions (Vassilev and Vassileva 2009).

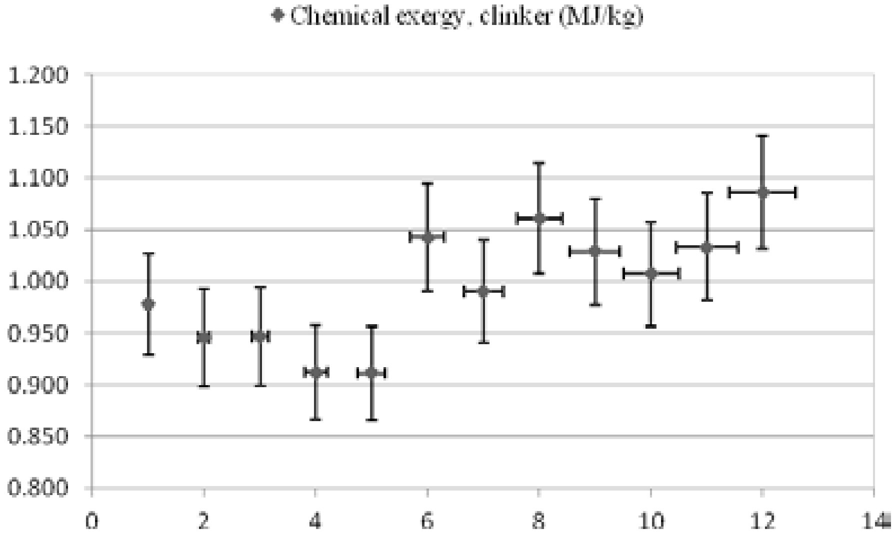

Figure B.3: Chemical exergy of clinker with different composition [Data source: IPPC 2010; Tokyay 1999]**.**

Table B.8: Typical compositions of phases in Portland cement clinker (% mass). Adopted from Taylor (1997).

Phase	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	Mn_2O_3	Fe_2O_3
Alite*	0.1	1.1	1.0	25.2	0.1	0.1	0.1	71.6	0.0	0.0	0.7
Belite*	0.1	0.5	2.1	31.5	0.1	0.2	0.9	63.5	0.2	0.0	0.9
Aluminate (cubic)*	1.0	1.4	31.3	3.7	0.0	0.0	0.7	56.6	0.2	0.0	5.1
Ferrite*	0.1	3.0	21.9	3.6	0.0	0.0	0.2	47.5	1.6	0.7	21.4
Aluminate (orthorhombic)	0.6	1.2	28.9	4.3	0.0	0.0	4.0	53.9	0.5	0.0	6.6
Aluminate (low Fe)	0.4	1.0	33.8	4.6	0.0	0.0	0.5	58.1	0.6	0.0	1.0
Ferrite (low Al)	0.4	3.7	16.2	5.0	0.0	0.3	0.2	47.8	0.6	1.0	25.4

* *Typical value for an ordinary Portland cement clinker with 1.65% MgO, 3.1%* Fe_2O_3, *and* $SO_3/(K_2O+Na_2O) < 1.0$. *The compositions of the phases may differ for clinker with different conditions.*

Table B.9: Thermochemical data

Species/ Compound	Name	Atomic/ molecular mas (g/mol)	ΔG (kJ/mol)	ΔH (kJ/mol)	ΔS (J/mol.K)	$\sum n_{ji}e_j$ (kJ/mol)	e^o_x (kJ/mol)	e^o_x (MJ/kg)	ΔH^o_{fus} (kJ/mol)	ΔH^o_{fus} (MJ/kg)	Cp (J/mol.K)	Ref
Al	Aluminum	26.982	0.0	0	28.3	888.40	888.4	32.926	10.789	0.3999	24.4	[1,2]
Al_2O_3	Alumuna	101.961	-1582.3	-1675.7	50.9	1782.70	200.4	1.965	111.4	1.0926	79.0	[1,2]
$Al_2O_3{\cdot}H_2O$=2AlO.OH	Boehmite	59.989	-914.1	-988.1		1109.40	195.3	3.256				[4,7]
$Al_2O_3{\cdot}3H_2O$=2Al(OH)$_3$	Gibbsite	78.004	-1154.9	-1,293.10		1364.40	209.5	2.686				[4,6]
H_2O (l)	Water	18.015	-237.1	-285.8	70	240.60	3.5	0.194	6.01	0.3336	75.3	[1,2]
AlF_3	Aluminum flouride	83.980	-1431.1	-1510.4	66.5	1655.97	224.9	2.678			75.1	[1,2]
$CaCO_3$	Limestone	100.087	-1129.1	-1207.6	91.7	1130.10	1.0	0.010	36	0.3597	83.5	[1,2]
$CaO{\cdot}Al_2O_3{\cdot}2SiO_2$	Anorthite (CaAl2Si2O8)	278.208	-4021.0	-4274.4		4092.71	71.7	0.258				
CO(g)	Carbon monoxide	28.010	-137.3	-110.523	197.9	412.37	275.1	9.821	0.833	0.0297	29.1	[1,2]

$CO_2(g)$	Carbon dioxide	44.010	-394.4	-393.513	213.6	414.25	19.9	0.451	9.02	0.2050	37.1	[1,2]
$CF_4(g)$	Tetraflouromethane	88.003	-888.5			1366.80	478.3	5.435				
$C_2F_6(g)$	Hexaflouromethane	138.009	-1257.3			2255.30	998.0	7.231				
Fe_2O_3	Hematite	159.688	-742.2	-824.2	87.4	758.70	16.5	0.103	138.6	0.8679	103.9	[1,2]
Na_3AlF_6	Cryolite	209.939	-3144.7	-3311.3		3472.60	327.9	1.562				[7]
NaOH	Caustic soda	39.997	-379.5	-425.6	64.5	393.80	14.3	0.358			59.5	[1,2]
$NaAlSiO_4$	Nepheline	142.055	-1972.4	-2087.6		1999.99	27.6	0.194				
SiO_2	Silica	60.085	-923.7	-910.7	41.46	931.57	7.9	0.131			44.6	[1,2]
TiO_2	Rutile	79.866	-888.8	-944	50.6	910.20	21.4	0.268			55.0	[1,2]
CaF_2	Flourspar	78.074	-1175.6	-1228	68.5	1187.00	11.4	0.146	30	0.3843	67.0	[1,2]
H_2SO_4	Sulfuric acid	98.079	-690.0	-814	156.9	853.40	163.4	1.666	10.71	0.1092	138.9	[1,2]
HF (g)	Hydroflouric acid	20.006	-275.4	-273.3	173.8	355.40	80.0	3.999				
C	Carbon anode	12.011	0.0	0	5.7	410.26	410.3	34.158	117	9.7413	8.5	[1,2]
S	Sulfur	32.066	0.0	0	32.1	609.60	609.6	19.011	1.72	0.0536	22.6	[1,2]
$AlCl_3$	Aluminum chloride	133.341	-628.8	-704.2	109.3	1073.70	444.9	3.337			91.1	[1,2]
$CaSO_4.2H_2O$	Gypsum	172.172	-1798.6	-2024		1815.20	16.6	0.096				[7]
$71\%N_2+29\%O_2$	Air	29.169	0.0	0		0.00		0.000				
Cu	Copper	63.546	0.0	0	33.2	134.20	134.2	2.112	12.93	0.2035	24.4	[1,2]
SiO_2	Silica	60.085	-923.7	-910.7		931.57	7.9	0.131	9.6	0.1598		[1,2,7]
$CuFeS_2$	Chalcopyrite	183.523	-178.5	-176.8		188.05	9.6	0.052	9.5	0.0518		[3,4]
Cl_2	Chlorine	70.906	0.0	0	223.1	123.60	123.6	1.743	6.4	0.0903	33.9	[1,2]
$CH_2{=}CH_2$	Ethylene	28.053	68.4	52.5	219.6	1292.70	1361.1	48.519	3.35	0.1194	42.9	[1,2]
HCl	Hydrochloric acid	36.461	-95.3	-92.3	186.9	179.80	84.5	2.318	2	0.0549	29.1	[1,2]
$C_2H_4Cl_2$	Ethylene dichloride	98.959	-92.7	-126.4	211.8	1459.62	1366.9	13.813	7.2	0.0728	126.3	[1,2]
O_2	Oxygen	31.999	0.0	0	205.2	3.97	4.0	0.124	0.44	0.0138	29.4	[1,2]

C_2H_3Cl (g)	Vinyl chloride monomer	62.498	53.6	37.3	264	1224.04	1277.6	20.443	4.92	0.0787	53.7	[1,2]
(-C_2H_3Cl-)	PVC	62.498		-94.1	59.4	1228.74	1228.7	19.660			14.6	[1,2]
C_2H_6	Ethane	30.069	-32.0	-84	229.2	1527.84	1495.8	49.747	2.72	0.0905	52.5	[1,2]
$C_{10}H_8$	Naphthalene	128.171	201.6	78.5	167.4	5053.40	5255.0	41.000	19.01	0.1483	165.7	[1,2]
NH_3	Ammonia	17.031	-16.4	-45.9	192.8	354.30	337.9	19.841	5.66	0.3323	35.1	[1,2]
SiH_4 (g)	Silane	32.118	56.9	34.3	204.6	1327.10	1384.0	43.091			42.8	[1,2]
Si_2H_6	Disilane	62.220	127.3	80.3	272.7	2417.70	2545.0	40.903			80.8	[1,2]
NaCl	Sodium chloride	58.443	-384.1	-411.2	72.1	398.40	14.3	0.245	28.16	0.4818	50.5	[1,2]
$CH_3-CH=CH_2$	Propylene (g)	42.080	63.0	21	267	1940.90	2003.9	47.621	3.003	0.0714		[1,2]
(-CH(CH_3)-CH_2-)	Polypropylene	42.080			78.99	1948.76	1948.8	46.311			88.0	[2,8]
$3CaO\cdot SiO_2$	Alite (C3S)	228.317	-3413.9			3681.37	267.5	1.171				[5]
$2CaO\cdot SiO_2$	Belite (C2S)	172.240				195.96	196.0	1.138				
$2SiO_2\cdot Al_2O_3\cdot 2H_2O$	S2AH2	258.161				109.86	109.9	0.426				
$4SiO_2\cdot Al_2O_3\cdot H_2O$	Pyrophyllite (S4AH)	360.316				138.95	139.0	0.386				
CF_4(g)	Tetraflouromethane	88.003		-933.6	261.6	478.28	478.3	5.435			61.1	[1,2]
C_2F_6(g)	Hexaflouromethane	138.001		-1344.2	332.3	998.00	998.0	7.232			106.7	[1,2]
$6CaO\cdot 2Al_2O_3.Fe_2O_3$	C_6A_2F	700.075				1209.11	1209.1	1.727				
$3CaO\cdot Al_2O_3$	Tricalcium aluminates	270.193				500.60	500.6	1.853				
$4CaO\cdot Al_2O_3.Fe_2O_3$	Tetra calcium alumino ferrite	485.959				303.96	304.0	0.625				
$4CaO\cdot Al_2O_3.Fe_2O_3$	C4AF	485.959				667.00	667.0	1.373				
$Al_2O_3.SiO_2$ (s)	AS	190.132				15.40	15.4	0.081				
$CaCO_3.MgCO_3$ (s)	Dolomite	184.401	-2167.9	-2327.9		2185.90	18.0	0.098				[7]
$CaO.Al_2O_3$ (s)	CA	158.039				275.40	275.4	1.743				
CaS	Calcium sulfide	72.144	-477.4	-482.4	56.5	1322.00	844.6	11.707	70	0.9703	47.4	[1,2]
CaO	Lime	56.077	-603.3	-634.9	38.1	713.50	110.2	1.965	80	1.4266	42.0	[1,2]

K_2O	Potassium oxide	94.196	-322.0	-361.5	94	735.10	413.1	4.386				[1,2]
MgO	Magnesium oxide	40.304	-569.3	-601.6	27	636.10	66.8	1.657	77	1.9105	37.2	[1,2]
$MgSO_4$	Magnesium sulfate	120.369	-1170.6	-1284.9	91.6	1208.50	37.9	0.315	14.6	0.1213	96.5	[1,2]
Na_2O	Sodium oxide	61.979	-375.5	-414.2	75.1	671.70	296.2	4.779	48	0.7745	69.1	[1,2]
$Fe_2O_3.SiO_2$	FS	219.773				18.40	18.4	0.084				
SO_2	Sulfur dioxide	64.065	-300.1	-296.8	248.2	613.50	313.4	4.892			39.9	[1,2]
2FeO·OH	Geothite	177.703	-489.2	-559.4		509.24	20.0	0.113				[4,7]
Fe	Iron	55.845	0.0	0	27.3	376.40	376.4	6.740			25.1	[1,2]
CuS	Copper sulfide	95.612	-53.6	-53.1	66.5	743.90	690.3	7.220			47.8	[1,2]
FeO	Iron oxide	71.844	245.1	-272	57.6	-118.10	127.0	1.768	24	0.3341		[1,2]
Fe_3O_4	Magnetite	231.533	-1015.4	-1118.4	146.4	1137.00	121.6	0.525	138	0.5960	143.4	[1,2]
$Al_2O_3.SiO_2.2H_2O$	Kaolinite(Al2Si2O5(OH)4)	198.077	-3793.9	-4119		3805.13	11.2	0.057				[6,8]
$SiCl_4$ (l)	Silicon tetrachloride	169.898	-619.8	-687	239.7	1101.70	481.9	2.836			145.3	[1,2]
H_2O (g)	Water	18.015	-228.6	-241.8	188.8	239.99	11.4	0.632			33.6	[1,2]
$CaSO_4$	Calcium sulfate	136.142	-1322.0	-1434.5	106.5	1330.20	8.2	0.060	28	0.2057	99.7	[1,2]
$CaCl_2$	Calcium chloride	110.984	-748.8	-795.4	108.4	836.70	87.9	0.792			72.9	[1,2]
CuO	Copper oxide	79.545	-129.7	-157.3	42.6	136.20	6.5	0.082	11.8	0.1483	42.3	[1,2]
$CuSO_4$	Copper sulfate	159.610	-662.2	-771.4	109.2	752.00	89.8	0.563				[1,2]
Cu_2O	Copper (I) oxide	143.091	-146.0	-168.6	93.1	270.40	124.4	0.869			63.6	[1,2]
Cu_2S	Copper (I) sulfide	159.158	-86.2	-79.5	120.9	878.00	791.8	4.975			76.3	[1,2]
$FeSO_4$	Iron (II) sulfate	151.909	-820.8	-928.4	107.5	993.80	173.0	1.139			100.6	[1,2]
FeS	Iron (II) sulfide	87.911	-100.4	-100	60.3	986.00	885.6	10.074	31.5	0.3583	50.5	[1,2]
FeS_2	Pyrite	119.977	-166.9	-178.2	52.9	1595.60	1428.7	11.908			62.2	[1,2]
H_2 (g)	Hydrogen	2.016	0.0	0	130.7	236.10	236.1	117.120	0.12	0.0595	28.8	[1,2]
H_2O_2 (l)	Hydrogen peroxide	34.015	-120.4	-187.8	109.6	120.40		0.000	12.5	0.3675	89.1	[1,2]

H_2S	Hydrogen sulfide	34.082	-33.4	-20.6	205.8	845.40	812.0	23.825	2.38	0.0698	34.2	[1,2]
CH_4	Methane	16.042	-50.5	-74.6	186.3	882.15	831.7	51.841			35.7	[1,2]
$Ca(OH)_2$	Calcium hydroxide	74.093	-897.5	-985.2	83.4	951.20	53.7	0.725			87.5	[1,2]
NH_4Cl	Ammonium chloride	53.492	-202.9	-314.4	94.6	534.20	331.3	6.194			84.1	[1,2]
$NaAlSi_3O_8$	Albite	262.225	-3704.5	-3927.6		3709.30	4.8	0.018				[7]
$CaCO_3 \cdot MgCO_3$	Dolomite	184.401	-2167.9	-2327.9		2191.13	23.2	0.126				[4,7]
SO_3	Sulfur trioxide	80.064	-371.1	-395.7	256.8	620.20	249.1	3.111	8.6	0.1074	50.7	[1,2]
$MgCO_3$	Magnesium carbonate	84.314	-1012.1	-1095.8	65.7	1050.00	37.9	0.450	59	0.6998	75.5	[1,2]
C_3H_8	Propane	44.096	-23.4	-103.8	270.3	2177.40	2154.0	48.848	3.5	0.0794	73.6	[1,2]
$NaAlO_2$	Sodium aluminate	81.970	-1127.0	-1133.09	70.4	1278.67	151.7	1.851				[7]
Na_2SO_4	Sodium sulfate	142.043	-1270.2	-1387.1	149.6	1291.60	21.4	0.151	23.6	0.1661	128.2	[1,2]
Na_2CO_3	Soda ash	105.988	-1044.4	-1130.7	135	1085.90	41.5	0.392	29.7	0.2802	112.3	[1,2]
Na_2SiO_3	Sodium silicate	122.064	-1462.8	-1554.9	113.9	1528.90	66.1	0.542	52	0.4260		[1,2]
$Na_2Si_2O_5$	Disodium silicate	182.149				66.70	66.7	0.366				[1,2]
$CaSiO_3$	Calcium metalsilicate	116.162	-1550.0	-1630	84	1573.60	23.6	0.203				
Ca_3SiO_5	Tricalcium silicate	282.320				219.80	219.8	0.779				
ZnO	Zinc oxide	81.379	-318.0	-348	44				52.3	0.6427		
MnO_2	Manganese(IV) oxide	86.937	-465.1	-520.0	53.1		21.2	0.244			54.1	
$MnSO_4$	Manganese(IV) sulfate	151.002	-228.4	-254.18			142.4	0.943				

[1] Lide 2005; [2]Szargut et al. 1998; [3] Valero Delgado 2008; [4] Ayres and Ayres 1999; [5] Trubaev and Besedin 2005; [6] John 2007; [7] Faure 1991; [8] NIST 2011

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Appendix C. Supporting information for

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Exergy calculation of polypropylene (PP) and polyvinylchloride (PVC) β value and elemental composition: To calculate the β values of PP and PVC equations C.1 is used. The elemental composition of hydrocarbons is taken from ECN (2009).

$$\beta = 1.0435 + 0.0159\ (H/C) \qquad \text{(C.1)}$$

Table C.1: Chemical exergy calculation of PP and PVC using elemental composition.

Name of material	C	H	O	N/ Cl	Cendres/ Ash	Total	Zo2/Zc < 2,67	Beta	LHV (MJ/Kg)	Exergy (MJ/Kg)	Process exergy (MJ/Kg)
PP	85.6	14.4			0.0	100.0	0.0	1.046	44.158	46.197	32.95
PVC	38.0	5.0		56.0	1.0	99.0	0.0	1.046	18.109	19.324	38.63

Table C.2: Exergy efficiency of crude petroleum extraction.

Input material and utility	Input exergy (MJ)	Useful product exergy (MJ)	Exergy efficiency (%)
Crude oil	43.867		
Electricity	0.440		
Distillate oil + residual oil	0.103		
Gasoline	0.029		
Natural gas	1.425		
Crude oil (extracted)		42.38	92.4

Table C.3: Exergy efficiency of crude petroleum refining.

Input material and utility	Input exergy (MJ)	Useful product exergy (MJ)	Exergy efficiency (%)
Crude oil	43.147		
Electricity	1.610		
Natural gas	0.478		
Residual oil	1.391		
LPG	0.037		
Petroleum distillate		42.38	90.8

Table C.4: Exergy efficiency of petroleum transport.

Input material and utility	Input exergy (MJ)	Useful product exergy (MJ)	Exergy efficiency (%)
Crude oil	42.384		
Electricity	0.100		
Distillate oil+ residual oil	1.188		
Crude oil		42.38	97.1

*Overall exergy efficiency of crude oil extraction, refining, and transport = 0.924*0.908*0.971*100 = 81.5%*

Table C5: Exergy efficiency of natural gas extraction.

Input material and utility	Input exergy (MJ)	Useful product exergy (MJ)	Exergy efficiency (%)
Natural gas	47.499		
Electricity	1.610		
Natural gas (fuel)	1.425		
Distillate oil + residual oil	1.017		
Gasoline	0.029		
Natural gas (extracted)		45.76	90.8

Table C6: Exergy efficiency of natural gas processing.

Input material and utility	Input exergy (MJ)	Useful product exergy (MJ)	Exergy efficiency (%)
Natural gas (feedstock)	45.989		
Electricity	0.240		
Natural gas (fuel)	1.498		
Gasoline	0.002		
Distillate oil+ residual oil	0.706		
Natural gas (processed)		45.76	94.5

Table C7: Exergy efficiency of natural gas transport.

Input material and utility	Input exergy (MJ)	Useful product exergy (MJ)	Exergy efficiency (%)
Natural gas (feedstock)	45.989		
Natural gas (fuel)	0.745		
Natural gas		45.99	98.4

Overall exergy efficiency of natural gas extraction, refining, and transport = 0.908*0.945*0.984*100 = 84.4%

Table C.8: Exergy inputs and outputs for the production of 1 kg PP in present industrial practices.

Process step	Input exergy (MJ)	Output exergy (MJ)	Exergy efficiency (%)
Naphtha production	81.16	61.40	75.7
Ethylene production	13.41	8.74	65.1
Propylene production	56.68	45.19	79.7
Propylene polymerization	50.60	46.31	91.5

Table C.9: Exergy inputs and outputs for the production of 1 kg PVC in present industrial practices.

Process step	Input exergy (MJ)	Output exergy (MJ)	Exergy efficiency (%)
Naphtha production	83.76	63.42	75.7
Ethylene production	77.21	50.28	65.1
Ammonia (NH_3) production	0.24	0.16	67.0
Chlorine (Cl_2) production	5.33	2.30	43.1
VCM production	36.74	21.99	59.8
Vinyl chloride polymerization	24.38	19.66	80.6

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