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Exergy cost of goods and services: a novel Input-Output based model including working hours

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Abstract

Understanding how to design sustainable industrial systems is fundamental to achieve the goal of a sustainable development. Industrial Ecology, a new engineering field, allows to evaluate the major causes of losses, in terms of materials and energy, among the life cycle stages of a target product, by means of the natural resource consumption accounting. In order to trace resource flows through industrial systems, the concept of ‘embodied exergy’ or ‘exergy cost’ arises as the more suitable numeraire to take into account various forms of energy and materials involved in the life cycle of goods and services. The exergy cost can be estimated using the Input – Output (IO) analysis. Indeed, an environmental extension of this economic framework allows to compute the exergy cost of the products under consideration.

As a first objective of this work, IO methodologies and the state of the art, have been presented and discussed.

Recently, in order to have a more comprehensive view of the environmental burdens associated with the provision of goods and services, several attempts have been made to take into account the resource consumption relating to factors of production such as capital and human labor. Nevertheless, in most of the proposed methods, consumption related to human labor is not strictly taken into account.

This work is an attempt to provide an extension of the IO framework for evaluating the external cost of working hours, in terms of natural resource consumption, in a coherent manner and without double counting.

The assumptions, the mathematical model and case studies will be introduced and explained. Finally, drawbacks, benefits and possible future developments concerning this methodology will be discussed.

keywords: exergy cost, human labor, input – output analysis, industrial ecology

Italian Abstract

Comprendere come progettare sistemi industriali sostenibili diventa fondamentale nell’ottica di uno sviluppo sostenibile. L’Ecologia Industriale, una nuova disciplina ingegneristica, permette di valutare le maggiori cause di perdita, in termini di materiali ed energia, nelle varie fasi del ciclo di vita di un determinato prodotto, attraverso la contabilità del consumo di risorse naturali. Al fine di tracciare i flussi di risorse all’interno dei sistemi industriali, il concetto di ‘embodied exergy’ o costo exergetico si presenta come numeraria più adatta per contabilizzare varie forme di energia e materiali impiegati nel ciclo di vita di beni e servizi. Il costo exergetico può essere stimato tramite l’utilizzo dell’analisi Input – Output (IO). Infatti, una estensione di questo strumento economico, in grado di elaborare gli oneri ambientali, permette di calcolare il costo exergetico dei prodotti in esame.

Come primo obiettivo di questo lavoro, i metodi IO e lo stato dell’arte, verranno presentati e discussi.

Recentemente, al fine di avere una visione completa degli oneri ambientali associati alla fornitura di beni ed servizi, numerosi tentativi sono stati compiuti per includere nel rendiconto il consumo di risorse legato a fattori di produzione quali capitale e lavoro umano. Tuttavia, nella maggior parte dei metodi proposti, il consumo di risorse relativo al lavoro umano non è stimato in maniera rigorosa. Questo lavoro è un tentativo di fornire una estensione dell’analisi IO per valutare il costo esternale delle ore lavorative in termini di consumo di risorse naturali, in modo coerente e senza effettuare conteggi multipli.

Le assunzioni, il modello matematico e casi studio verranno presentati e spiegati. Infine, gli svantaggi, i benefici e i possibili sviluppi futuri di questa metodologia verranno discussi.

parole chiave: costo exergetico, lavoro umano, analisi input – output, ecologia industriale

Estratto in lingua italiana

L’impatto del consumo di risorse naturali

La storia umana è stata indiscutibilmente correlata al controllo, all’estrazione e l’uso delle risorse naturali. Nelle ultime decadi, tuttavia, lo sfruttamento delle risorse naturali si è divenuto sempre più marcato, causando problemi ambientali come il cambiamento climatico, la perdita di biodiversità, la desertificazione e la degradazione degli ecosistemi.

Il concetto di sviluppo sostenibile è nato a seguito della consapevolezza dell’esaurimento, relativamente precoce, delle risorse naturali a nostra disposizione.

Sviluppo sostenibile significa: ‘soddisfare le necessità del presente senza compromettere la capacità delle generazioni future di incontrare i propri bisogni’ in ottica sia economica, sociale ed ambientale.

Un’espressione del concetto di sviluppo sostenibile è nell’Ecologia Industriale. Questo nuovo campo ingegneristico, si pone l’obiettivo di applicare la nozione di sostenibilità a sistemi ambientali ed economici.

Migliorare e mantenere la qualità dell’ambiente che ci circonda, riducendo l’impatto delle attività umane sulla sfera biofisica è il proposito principe di questa nuova disciplina. Difatti, l’Ecologia Industriale raggiunge tale obiettivo cercando di ottimizzare l’uso delle risorse naturali quali materiali, energia ed ecosistemi, che vengono impiegati nei sistemi industriali, a livello settoriale, regionale, nazionale.

Le numerarie per contabilizzare le risorse e le metodologie con le quali è permesso rendicontarle, sono gli strumenti che l’Ecologia Industriale mette a disposizione al fine di valutare l’impatto ambientale dei sistemi industriali.

Il dibattito su quale sia la migliore numeraria per contabilizzare lo sfruttamento di risorse naturali è ancora in atto. La capacità di prendere in considerazione varie forme di energia e materiali, diviene fondamentale per avere una visione completa ed esaustiva nella valutazione dell’impatto complessivo.

L’exergia, tra le altre numerarie, ha numerosi benefici tra i quali l’abilità di poter distinguere la qualità energetica, in accordo con il secondo principio della termodinamica, e la possibilità di misurare flussi di materia ed energia in termini comparabili. Inoltre, essa è capace di valutare le perdite termodinamiche all’interno di un processo, fornendo uno spunto per migliorare ed ottimizzare le catene di produzione.

Varie metodologie sono state implementate al fine di calcolare il consumo di risorse legato alla produzione o al ciclo di vita di un singolo prodotto. Tra le altre, l’analisi Input – Output di presenta come strumento ideale per compiere questa funzione.

Exergia ed analisi Input – Output sono punti cardini dell’Ecologia Industriale e sono gli strumenti con cui si articola e prende corpo questa tesi, la quale si pone l’obiettivo di rendicontare il costo esternale legato alle ore lavorative, in termini di consumo di risorse naturali.

Il concetto di energia ed exergia ‘incorporata’ in beni e servizi

Il consumo di risorse naturali è allocato ad un determinato prodotto durante ogni fase del suo ciclo di vita. Le risorse cumulate impiegate nel ciclo di vita di un bene o di un servizio sono anche dette anche ‘embodied’ ovvero ‘incorporate’ in quel bene o servizio.

Durante la crisi petrolifera degli anni ’70, molti studiosi e ricercatori si interessarono all’analisi energetica per valutare gli effetti di un uso intensivo dei combustibili fossili sull’ambiente. Studi come quelli di Bullard e Hereenden miravano a valutare il costo energetico relativo ai beni e servizi erogati dall’economia americana, al fine di determinare i prodotti con il più alto consumo di energia primaria. In questi anni è emerso per la prima volta il concetto di ‘embodied energy’. Negli anni successivi, questo concetto è stato esteso anche ad altri indicatori ambientali quali materiali, emissioni, uso del suolo ecc.

Negli ultimi anni, il concetto di energia ‘embodied’ nei beni e servizi è stato adattato all’exergia, al fine di sviluppare un’analisi in linea con il secondo principio della termodinamica e in modo da poter comparare materiali ed energia con la stessa numeraria.

In parallelo sono state sviluppate varie metodologie e, alla fine degli anni novanta, la comunità scientifica ha reclamato una standardizzazione dei metodi con cui determinare le risorse ‘incorporate’ nei prodotti.

La metodologia del Life Cycle Assessment (LCA) permette di valutare gli oneri ambientali associati alle varie fasi del ciclo di vita di un prodotto, attraverso procedure standard riconosciute a livello internazionale. Gli sviluppi futuri di questa tecnica, riguardano la possibilità di effettuare un’analisi del ciclo di vita di un prodotto, integrando le tre dimensioni della sostenibilità nel Life Cycle Sustainability Assessment (LCSA).

La nozione di embodied energy o embodied exergy può essere espressa in una prospettiva LCA. Molti, infatti, sono i metodi sviluppati al fine di rendicontare i flussi di energia o exergia cumulati. In questo lavoro sono state analizzate la ‘Net Energy Analysis’ di Bullard e Costanza, l’analisi emergetica di Odum, la Cumulative Exergy Consumption (CExC), l’Exergetic LCA e l’Extended Exergy Accounting (EEA) di Sciubba.

Tuttavia, delle metodologie sopracitate, solo alcune includono il consumo di risorse relativo a fattori di produzioni quali capitale e lavoro umano, ponendosi in un’ottica di LCSA. In particolare, poiché questo lavoro si focalizza sul consumo di risorse relativo al costo esternale delle ore di lavoro, sono state discusse le metodologie che prevedono di includere nel rendiconto tale fattore di produzione. Nella ‘Net Energy Analysis’ ciò è possibile attraverso l’utilizzo della metodologia Input – Output; nell’analisi emergetica si definisce una emergia per unità di lavoro, mentre nell'EEA l'exergia 'embodied' nel lavoro umano è calcolata tramite un coefficiente econometrico. Per contro, Szargut, uno dei pionieri della CExC, dimostra che rendicontare il consumo di risorse legato alle ore uomo, significa effettuare un doppio conteggio poiché vi è un ricircolo di risorse all'interno della società.

Metodi per calcolare l'Embodied Exergy

I metodi per calcolare le risorse assorbite nei beni e servizi sono essenzialmente tre: l'analisi di processo, l'analisi input – output e l'analisi ibrida.

L'analisi di processo permette di valutare i flussi diretti e indiretti di risorse impiegate al ciclo di vita di un prodotto, valutando sia le risorse dirette sia le risorse necessarie ad attivare i processi 'a monte' di quello che realizza il prodotto finale. Tuttavia, questo metodo non permette di valutare tutti gli oneri in maniera completa poiché i processi che presentano input di risorse trascurabili vengono omessi dall'analisi, al fine di evitare un'ulteriore raccolta dati su processi non rilevanti.

L'analisi Input – Output (IO) è stata introdotta dal premio Nobel Leontief come strumento economico per tracciare flussi monetari all'interno di una economia. Tali flussi sono rappresentati tramite una tabella che, solitamente, è suddivisa in una matrice che contiene i flussi scambiati tra i settori dell'economia e un vettore relativo alla domanda finale (consumi famiglie, esportazioni, spese governative ecc.).

Il modello matematico permette di calcolare i contributi diretti e indiretti necessari alla realizzazione di un prodotto di un determinato settore, attraverso la matrice inversa di Leontief. L'analisi può essere estesa ad input esogeni quali risorse naturali o, in questo caso, exergia.

Molti sono i modelli di tavole IO che è possibile implementare. Una prima classificazione può essere fatta in base alle unità di misura utilizzate per tracciare i flussi all'interno dei sistemi: le classiche tabelle IO sono rappresentate in termini monetari; le tabelle IO fisiche utilizzano di solito unità di massa; tavole in unità ibride permettono di assegnare ad ogni settore l'unità di misura che meglio si adatta al prodotto di quel determinato settore.

Lo stato dell'arte dell'analisi IO si sviluppa in metodologie quali l'Economic Input – Output Life Cycle Assessment (EIOLCA) e l'Environmentally Extended Input – Output (EEIO). Le ultime presentano tavole in termini monetari e gli oneri ambientali sono calcolati attraverso una matrice diagonale, associata al modello matematico di base di Leontief, che rappresenta gli input esogeni in termini di risorse naturali. Sotto determinate ipotesi, i vantaggi di usare metodologie di questo genere risiedono nel fatto di poter sfruttare dati largamente disponibili sui flussi monetari piuttosto che dati su flussi fisici scambiati tra settori, molto più difficili da reperire.

L'analisi IO e l'analisi di processo hanno la stessa struttura matematica. Tuttavia, essi discostano per il differente livello di aggregazione dei dati.

L'analisi di processo, infatti, necessita di dati di processo specifici, mentre l'analisi IO è una analisi a livello di settore. Per questo motivo il modello IO permette di effettuare un'analisi completa che interessa tutti i settori dell'economia: per contro l'analisi di processo si limita a valutare solo alcuni processi a monte di quello principale.

L'ultimo metodo per valutare il costo 'embodied' delle risorse, adopera una combinazione dell'analisi di processo e dell'analisi IO. L'analisi ibrida infatti, utilizza entrambe le metodologie per sfruttare sia i vantaggi dell'analisi di processo, sia i vantaggi di una analisi IO.

Il costo exergetico del lavoro umano

Il problema dell'assegnazione di un costo in termini di consumo di risorse alle ore uomo è rimasto per molto tempo irrisolto.

L'ecologia e l'economia divergono nel trattamento di questo fattore di produzione. Se, infatti, in economia il lavoro umano è un input indipendente, dal punto di vista ecologico esso è un input intermedio, in quanto il lavoro umano, in termini di ore lavorate, è reso disponibile in seguito ad un consumo di risorse.

Inoltre, come evidenziato in metodi come l'EEA, considerare anche i costi dell'esternalità relativi a fattori di produzione quali lavoro e capitale è un passo necessario per tentare di collegare economia e termodinamica. Questa tesi propone un metodo per valutare il costo esternale delle ore lavorate, in linea con i principi della termodinamica.

Al fine di raggiungere tale obiettivo, viene proposto l'uso di una metodologia IO modificata per rendere endogeno il costo esternale delle ore di lavoro nelle tabelle IO e permettere il suo calcolo in termini di costo exergetico.

La numeraria scelta per calcolare il consumo primario di risorse naturali è l'exergia, la quale permette di distinguere la qualità energetica e prendere in considerazione varie forme di energia. Tuttavia, poiché l'obiettivo dell'analisi è valutare il costo exergetico nell'ottica della sostenibilità, è stata conteggiata solo l'exergia primaria da fonti non rinnovabili.

Il modello IO di base, è una tabella che contiene i flussi economici scambiati tra settori e la domanda finale in termini monetari. Attraverso la matrice diagonale degli input esogeni affiancata al modello, è possibile valutare gli oneri exergetici associati ad ogni classe di domanda finale. Esso è una riproduzione di metodi IO già citati nello stato dell'arte come l'EIOLCA e l'EEIO. Per questo verrà definito come modello "base".

Il modello IO, che rende endogene le ore di lavoro, è proposto in unità ibride e permette di internalizzare una parte della domanda finale delle famiglie, la quale rappresenta l'input di beni e servizi necessari al sostentamento dei lavoratori. Quest'ultimi producono ore di lavoro come output verso ogni settore dell'economia. In questo modo, il modello è capace di creare un nuovo 'settore manodopera' all'interno della tabella IO, il quale riceve risorse in input e produce lavoro come output. Il modello permette di calcolare il costo exergetico specifico della singola ora lavorativa e il costo exergetico dei beni e servizi, tenendo conto delle risorse, valutate in termini exergetici, consumate dai lavoratori.

E’ stato proposto anche un ulteriore modello, il quale presenta la stessa struttura del modello precedente, sebbene consideri come output del ‘settore manodopera’ il valore aggiunto in termini monetari attribuito dal lavoro umano ai prodotti dell’economia. In questo modo il costo exergetico specifico sarà riferito ad una unità monetaria invece che alla singola ora lavorativa.

Il modello IO di base e i due modelli IO proposti sono stati formalmente descritti dal punto di vista matematico e le differenze che intercorrono tra loro, sono state presentate e discusse.

Casi studio

Le tecniche IO proposte sono state applicate a casi studio di diversa natura, al fine di illustrare tutti i possibili campi di applicazione.

Il primo caso studio è un confronto tra tre paesi: USA, Cina e Italia. Sono stati implementati sia il modello “base”, sia il modello che integra il costo esternale legato al consumo di risorse dei lavoratori all’interno delle tavole IO. Le tavole IO utilizzate sono riferite all’anno 2009 e sono composte da 35 settori. Attraverso l’applicazione dei modelli è stato possibile valutare il costo exergetico specifico e il costo exergetico totale, per ogni prodotto di settore e per ogni economia osservata. In questo modo è possibile valutare quali sono i settori con il più alto costo exergetico per le tre economie. Inoltre, in seguito all’applicazione del secondo metodo, che include il consumo di risorse correlato al lavoro umano, è stato possibile confrontare i valori del costo exergetico specifico della singola ora lavorativa per ogni paese.

Il secondo caso studio impiega tavole IO per un range di anni dal 2000 al 2006, aggregate per 27 paesi dell’Unione Europea. Le tavole IO si compongono di 59 settori. L’implementazione di questo caso studio, permette di valutare i cambiamenti nel tempo del costo exergetico specifico e totale per ogni settore. Inoltre è possibile determinare la variazione del costo exergetico relativo all’ora lavorativa negli anni. E’ stato evidenziato come, nel corso degli anni, poiché la tecnologia non varia, il costo exergetico dei beni e servizi subisce piccole variazioni. Una ulteriore analisi è stata effettuata comparando il costo exergetico dei beni relativi al settore ‘Energia elettrica, gas, vapore e fornitura di acqua calda’ con l’inverso del prezzo dei beni relativi a questo settore, per ogni anno, dal 2000 al 2006.

Il terzo ed ultimo caso studio, converte una analisi di Life Cycle Cost applicata ad una turbina eolica, in una analisi di costo exergetico attraverso l’implementazione della tecnica IO. Sono stati osservati due scenari: il primo non prevede l’utilizzo del Condition Monitoring System (CMS), componente che permette di ridurre gli oneri legati alla manutenzione nel corso del ciclo di vita della turbina alla luce di un costo di investimento maggiore. Al contrario, la

turbina eolica del secondo scenario è dotata del sistema CMS. E’ stato riscontrato che, usando costi exergetici specifici del modello IO base, il primo scenario è più conveniente del secondo in termini di costo exergetico totale, in quanto tale modello non pesa la manodopera impiegata nella manutenzione. Diversamente, con l’applicazione del modello IO che calcola il costo exergetico delle ore di lavoro, il secondo scenario diviene meno costoso in termini di exergia primaria consumata, in quanto le ore di manodopera che il sistema CMS permette di risparmiare, sono rendicontate.
L’applicazione dei modelli ai tre casi studio ha permesso di valutare le possibili analisi che possono essere effettuate impiegando la tecnica IO e ha evidenziato i vantaggi offerti dal metodo IO che include il costo esternale delle ore lavorate rispetto al metodo IO base.

Conclusioni

Interiorizzare il costo esternale delle ore uomo all’interno delle tavole IO, permette di assegnare un costo exergetico al lavoro umano e può essere un primo passo verso la risoluzione delle divergenze tra economia ed ecologia relativamente al trattamento di questo fattore di produzione.
Il metodo proposto è adatto a:

- calcolare il costo exergetico della manodopera evitando doppi conteggi,
- calcolare le ore di lavoro ‘embodied’ nei beni e servizi,
- fornire risultati riproducibili,
- fornire il costo exergetico specifico e totale dei beni e servizi attraverso l’uso di semplici coefficienti ottenuti con la tecnica IO,
- calcolare il costo exergetico di nuovi prodotti.

Inoltre il metodo permette sviluppi futuri quali:

- la possibilità di assegnare un costo exergetico differente alle ore lavorative di diverse classi sociali, suddividendo in modo più esclusivo il fabbisogno di ogni tipo di lavoratore,
- la possibilità di modificare la domanda di beni e servizi richiesti dai lavoratori arbitrariamente, in base ad assunzioni differenti,
- l’opportunità di utilizzare numerarie diverse dall’exergia per il calcolo del consumo di risorse primario,
- la possibilità di integrare i risultati ottenuti con questa tecnica con metodologie che mirano a calcolare il costo exergetico dei prodotti, come ad esempio, l’EEA.

Lo sviluppo di questa tecnica può, inoltre, apportare benefici alla nuova disciplina dell’Ecologia Industriale, enfatizzando le interazioni tra esseri umani e ambiente. In aggiunta, questo strumento può delinearsi come un progresso importante nell’ottica dell’integrazione delle tre dimensioni della sostenibilità, in quanto sia aspetti economici, sociali ed ambientali sono stati elaborati in questa analisi.

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Introduction

Traditional exergy analysis consists in the application of the exergy balance to a defined control volume, in order to highlight losses, in terms of exergy destruction, and efficiencies of processes.

Usually, exergy analysis is applied to the operation phase of a system, since it is capable of quantifying the real sources of inefficiency within the system, and allowing for a comparison of different energy systems [1].

However, exergy analysis can be extended to every phase of the life cycle of any product and recently, it has been adopted in life cycle-based methods.

Throughout the entire life cycle of a product or a system, there are other ‘‘possible resources’’ than material and energy that need to be accounted for, such as externalities relating to the factors of production: labor and capital.

It is clear that exergy analysis cannot be used ‘‘as is’ for evaluating these externalities [1].

In order to have a complete and a comprehensive analysis of all the resources involved in the life cycle of a product, including all the factors of production, proper exergy models are necessary to take into account energy and materials resources, labor and monetary inflows. Fig. 0.1 shows all the resources that cross the system boundary, which is differently defined by different methods.

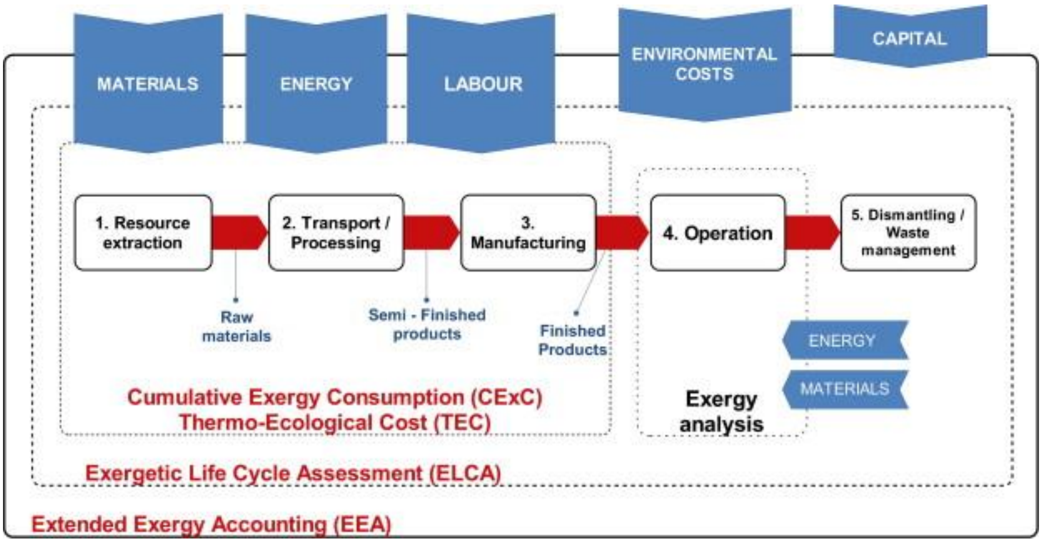

Figure 0.1: Spatial and temporal domains for the life cycle resource cost approach methods [1].

Novel methods, such as Extended Exergy Accounting (EEA), result in a system of cost equations in which inhomogeneous quantities like labor, material and energy flux, capital, are all homogeneously expressed in primary exergy equivalents.

This work seeks to provide an alternative method to evaluate the exergy equivalent of labor through the use of the Input – Output (IO) Analysis.

Nevertheless, the exergy equivalent of labor, calculated by using the IO model, is strictly defined in relation to the final product under consideration. This concept is expressed in the mathematical model of the IO analysis, in the example 4.4.3 and in the third case study.

In addition, since IO model is capable of allocating primary resources to final products, the exergy cost of goods and services will be also calculated using this approach.

1. Evaluating Natural Resource Consumption

Human history has always been closely related to the control, extraction and use of natural resources. However, over the past decades demand for natural resources has increased, causing environmental problems such as climate change, biodiversity loss, desertification, and ecosystem degradation [2].

Over the past 50 years, humans have used natural resources more rapidly than any comparable period in their history, changing ecosystems and losing the diversity of life on Earth.

The concept of a sustainable development can help to improve the management of natural resources and reduce the environmental pressure of humans on the ecosystems.

Qualitatively, the concept of sustainable development is simple enough: the natural resources of the Earth are limited. The present lifestyle of the developed nations is not sustainable on account of their disproportionately large per capita resource consumption that results in environmental degradation and societal inequity [3].

In broad terms, the concept of sustainable development is an attempt to combine growing concerns about a range of environmental issues with socio-economic issues [4].

The concept of sustainable development expresses itself in Industrial Ecology. Industrial Ecology is a new concept emerging in the evolution of environmental management paradigms and springs from interests in integrating notions of sustainability into environmental and economic systems [5].

The name Industrial Ecology suggests the fields that this branch of knowledge takes under consideration. Industrial Ecology is ‘industrial’ in that it focuses on product design and manufacturing processes, whereas Industrial Ecology is ‘ecological’ because places human technological activities in the context of the larger ecosystems that support it, examining the sources of resources used in society [6].

One of the objectives of Industrial Ecology is setting methods for resource consumption accounting. Indeed, the shape of a future resource accounting system is gradually emerging, in response to new perspectives introduced by Industrial Ecology [7]. Firstly, studies inspired by energy crisis in the late 1970s, focused on ‘net energy’ accounting. These studies stimulated interests in a unit that reflects also the quality of mass, that is exergy. Exergy, instead of energy, is also a useful measure for other resources, including biomass and minerals, and it can be also measured the potential reactivity of material wastes and pollutants [7], providing a more suitable framework for resource accounting.

This chapter will describe the concept of sustainable development, then the subject of Industrial Ecology will be introduced and explained and exergy as numeraire for resource accounting, will be described and critically analyzed, from a sustainable point of view.

1.1 The concept of Sustainable Development

Sustainable development has been adopted by the United Nations as a guiding principle for economic, environmental and social development that aspires to meet the needs of the present without compromising the ability of future generations to meet their own needs and an equitable sharing of environmental costs and benefits of economic development between and within the countries [8].

Sustainability integrates three fundamental dimensions considering environmental, social and economic aspects. These three dimensions are also denoted as pillars of sustainability. The three pillars of sustainability can be also viewed as corners of a triangle shown in fig. 1.1. The latter illustrates the objectives of every pillar: biological system aims at preserving genetic diversity, resilience and productivity; social system aims at providing social cohesion, cultural diversity and empowerment; the economic system aims at generating growth and equity through efficiency. The concept of sustainable development seeks to make a trade-off between all these goals belonging to every dimension of sustainability.

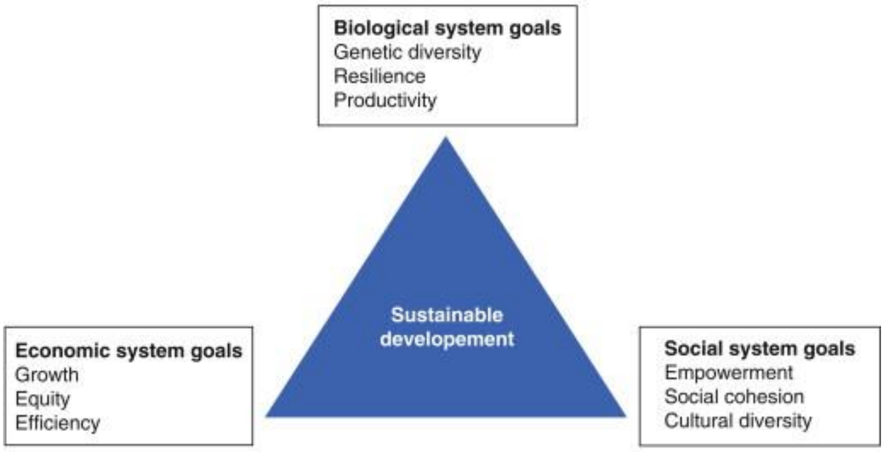

Figure 1.1: The objectives of sustainable development [9].

The term ‘Sustainable Development’ was firstly used in the publication of the Brundtland Commission’s Report on the global environment and development in 1987 [10]. As stated in this publication, the term ‘Sustainable Development’ contains within it two key concepts [11]:

- the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and
- the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.

Sustainability is based on these two concepts, which focus the attention of the global community on human beings and the environment.
In that report also the strategies to reach the sustainable development were described in order to promote harmony among human beings and between humanity and nature [11]:

- a political system that secures effective citizen participation in decision making.
- an economic system that is able to generate surpluses and technical knowledge on a self-reliant and sustained basis
- a social system that provides for solutions for the tensions arising from disharmonious development.
- a production system that respects the obligation to preserve the ecological base for development,
- a technological system that can search continuously for new solutions,
- an international system that fosters sustainable patterns of trade and finance, and
- an administrative system that is flexible and has the capacity for self-correction.

As it is possible to see from these guidelines, the concept of sustainable development includes both the techno-sphere and the biosphere.
The Brundtland Commission’s report has made a great contribution by emphasizing the importance of sustainable development and forcing it to the top of the agenda of the United Nations [12]. These efforts made by Brundtland Commission, culminated with the first Earth Summit in Rio de Janeiro in 1992.
At the Earth Summit in 1992, the international community adopted the concept of “sustainable development” which brought together development and environment concerns, and suggested to address them in an integrated way.
Chapter 40 of Agenda 21, the action plan adopted in 1992 at the United Nations Conference on Environment and Development in Rio de Janeiro, calls on countries, as well as international, governmental and non-governmental organizations, to develop indicators of sustainable development that could provide a solid basis for decision-making at all levels. This mandate was reflected in the decision of the Commission for Sustainable Development in

1995 to adopt an indicators work programme in order to identify the following indicator themes [13]:

- Poverty
- Governance
- Health
- Education
- Demographics
- Natural hazards
- Atmosphere
- Land
- Oceans, seas and coasts
- Fresh water
- Biodiversity
- Economic development
- Global economic partnership
- Consumption and production patterns

Ten years after the Earth Summit in Rio, in 2002, the Johannesburg Summit presented an opportunity for leaders to adopt concrete steps and identify quantifiable targets for better implementing the concept of sustainable development introduced with Earth Summit in 1992.

After these steps, sustainable development reshaped the policies and the practices of global manufacturing firms. Corporations seek sustainability through designing environmentally and socially responsible products, processes and technologies with a full awareness of life cycle costs. Industrial Ecology, the new science, provides a useful perspective to support this kind of sustainable development.

1.2 Industrial Ecology

1.2.1 Definition, goals and brief history

Allenby [14] has referred to Industrial Ecology as the 'science of sustainability'.

Industrial Ecology is a new approach to the industrial design of products and processes and the implementation of sustainable manufacturing strategies. It is a concept in which an industrial system is viewed not in isolation from its surrounding systems but in concert with them [15].

Robert White, the former president of the US National Academy of Engineering, defines Industrial Ecology as 'the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources' [6].

As shown in fig. 1.2, Industrial Ecology is included within the sphere of socio – economic policies, ecology and finally in the concept of sustainability.

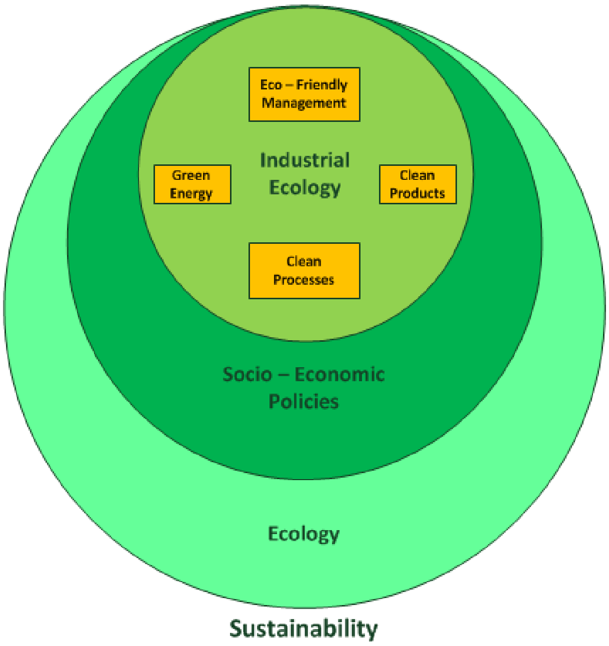

Figure 1.2: From Industrial Ecology to sustainability [16].

The overall objective of Industrial Ecology is to improve and maintain environmental quality reducing human impact on the biophysical environment. Indeed, Industrial Ecology aims at optimizing resource use: it asks how resource use, which cross the system boundary (groups of firms, regions, sectors and so on), might be optimized, where resource use includes both materials and energy (as inputs) and ecosystems.

Industrial Ecology has two functions [6]: a descriptive function when it seeks to describe and characterize human–environment interactions, but not necessarily to alter them; and a normative function when it seeks to improve upon human life and environment implementing new policies.

The idea about Industrial Ecology began to emerge over the 1970s, when some works of the pioneer of this field, Robert Ayres, were published. Ayres and colleagues began to examine flows of materials and energy in systems. About the same time, in Belgium, the concept of Industrial Ecology was used to trace the flows of materials and energy within the Belgian economy, instead of the usual monetary flows [17]. However, the concept of Industrial Ecology was not yet defined. The situation changed in 1989 when Frosch and Gallopoulos published a paper [18] in which they reported an industry in the form of an ecosystems composed by flows of materials and interconnections between the processes as shown in fig. 1.3. They called it ‘industrial ecosystem’. Ever since, the concept of Industrial Ecology was developed until the present day.

Figure 1.3: Industrial Ecosystem cycle in Frosch and Gallopoulos work [18].

1.2.2 Resource accounting and methodology

Understanding the structure and functioning of the industrial or societal metabolism is at the core of Industrial Ecology [19]. In order to reach that goal, Industrial Ecology claims for numeraires for resource accounting and methods to trace flows of materials within the economy and ecosystems.

The term “numeraire” refers to a unit of measure whereby the accounting is standardized.

Until now, Industrial Ecology was based on Material Flow Analysis (MFA), Substance Flow Analysis (SFA) and Physical input – output accounting [20]. Nevertheless, several attempts have been made to reduce all kinds of material and energy to one single numeraire [7]. Emergy, proposed by Odum, is defined as ‘the work previously done to make a product or service’ [21], in order to evaluate both energy quality and different materials or contributions with a single numeraire. However, the precursor work included in emergy is historical: the time scale is geological and therefore difficult to assess. On the other hand, Ayres, the pioneer of Industrial Ecology, in several works [22, 23] claims for the use of exergy as numeraire in order to fulfill the second law of thermodynamics and describe in a better way economic processes. Indeed, exergy is not conserved and it is a useful common measure of resource quality, as well as quantity, applicable to both materials and energy. Thus, exergy can be used to measure and compare resource inputs and outputs, including wastes and losses. Moreover, since exergy is not conserved it is truly consumed in economic processes [23]. In any case, the debate on the choice of the best numeraire for resource accounting is still opened [7].

As regards methods to account for resources, Faye Duchin [24] proposed the input – output analysis (IOA) as an important formal model within structural economics that can trace the stocks and flows of energy and other materials from extraction through production and consumption to recycling or disposal, providing quantitative answers to the kinds of questions raised by Industrial Ecology [25]. Eventually, IOA gained visibility, from an Industrial Ecology point of view, when some approaches that merge Life Cycle Assessment and IOA, such as Economic Input – Output Life Cycle Assessment (EIOLCA), have been developed.

Suh [26], highlights the following advantages related to the use of the IOA in Industrial Ecology:

- Both input–output economics and industrial ecology place strong emphasis on real world data.
- IOA has always had the ambition to facilitate interdisciplinary research by connecting different disciplines, encompassing price and quantity relationships.
- As compared to industrial ecology, input–output economics is a mature scientific field.
- From a practical perspective, the input–output table provides valuable statistical information for industrial ecologists.

These advantages lead Suh to state that the cooperation between IOA and Industrial Ecology is essential for the development of these two disciplines [26].

1.2.3 The role of Labor in Industrial Ecology

The treatment of Labor is an interdisciplinary theme. However, according to the purpose of this work, Labor is not intended as the moral value on which every society is based, but as a factor of production as intended in Solow model.

Both Ecology and Economics are involved in the debate concerning the treatment of this factor of production [7]. Economists argue that every kind of good and service required by workers (for instance food, clothes, education etc.) is defined as consumption and cannot be included in the cost of production. In effect, economic theories regards human labor as an independent input: human labor contributes to production, but its creation is in the past and lies outside the domain of the analyst. Therefore, in economic view, workers are consumers and considering consumption as a part of production would thus be double counting.

Ecologists, by contrast, include the energy (exergy) consumed by workers as a part of the energy (exergy) cost of production. However, energy (exergy) consumed by workers is difficult to assess considering the time domain needed to create workers’ skills.

In any case, it is clearly to understand that workers consume resources to enable their labor and this consumption has to be taken into account.

In evidence of this fact, Ayres [27] states that labor and capital have to be considered not independent inputs, but intermediate inputs since resources are embodied both in labor and in capital. Indeed, the only direct cost of labor to the firm does not reflect the cost of complementary capital (and exergy) required to utilize that labor. Similarly, the direct cost of capital equipment does not reflect the cost of the complementary energy (exergy) inputs required to operate that capital. For these reasons, and since ‘economic theory does not count the food, clothing, housing and other consumption by workers - nor their education and training - as part of the cost of production, although it does count the energy consumed by labor-saving machines in the production process’ [7], Ayres claims for inconsistency in economic paradigm.

1.3 Exergy as numeraire for calculating resource consumption

In the previous paragraph the possible numeraires for resource consumption accounting have been introduced. Ayres, one of the pioneer of the Industrial Ecology, identified exergy as the most suitable for this task.

It is well known that exergy accounting provides a wide and clear vision of the use and degradation of energy and subsequently of natural resources [28]. Exergy allows to take into account any kind of material with respect to some reference condition. Its relationship with the Industrial Ecology gives the possibility to understand processes in nature and society.

Since exergy complies with the second law of thermodynamics, it allows to quantify and locate thermodynamic losses and allows us to concentrate on the thermodynamically relevant part of the energy, namely ‘useful’ energy [28].

Defining Exergy

Exergy is a thermodynamic function that contains both the first and the second law of thermodynamics. It provides a quantitative basis to measure the degradation of energy in conversion processes [1]. It has been interpreted as ‘available’ energy by Keenan [29]. Z. Rant proposed the term exergy for the first time referring to the ‘technical working capacity’ [30]. However, it can be found in literature as availability, available energy, essergy, utilizable energy, work potential, available work, convertible energy, etc.

Among the definitions provided by literature, the most common definition, referring to fig. 1.4, is:

“(Exergy is) the maximum theoretical useful work obtained if a system S is brought into thermodynamic equilibrium with the environment E by means of processes in which the interacts only with this environment” [31].

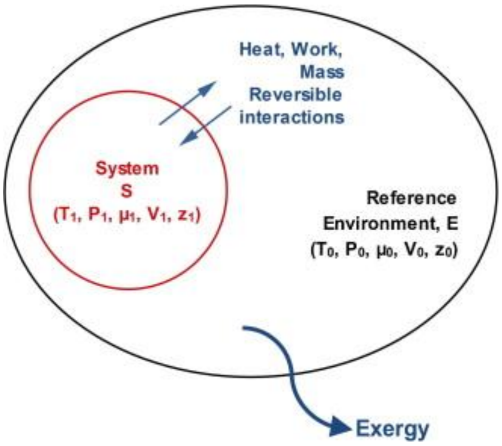

Figure 1.4: For the definition of exergy [1].

It is clear to understand the importance of evaluating energy, matter and every system on the basis of a single standard: the ability to make a useful work. The opportunity for doing useful work is given when two system at different states, are placed in communication. If one of the two system can be idealized as the environment, whereas the other one is the system under consideration, exergy is the maximum theoretical useful work obtainable when the systems interact to equilibrium. Exergy is a measure of the departure of the state of the system from that of the environment [32]. Clearly, in order to assign a value to exergy, the environment has to be specified.

Reference environment

If exergy is defined as the maximum work potential of a material or of a form of energy in relation to its environment, then the environment must be specified.

The environment is a very large body or medium in the state of perfect thermodynamic equilibrium [33].

The environment consists of common substances existing in abundance within the Earth’s atmosphere, oceans, and crust. The substances are in their stable forms as they exist naturally, and there is no possibility of developing work from interactions-physical or chemical-between parts of the environment [32].

Another concept that has to be introduced is the dead state. The latter is a state of the system. At the dead state, the conditions of mechanical, thermal, and chemical equilibrium between the system and the environment are satisfied, and there is no possibility of an interaction between them and there is no possibility of a change within the system or the environment. Another type of equilibrium is given by the “restricted dead state” or environmental state [33], which refers to the condition of mechanical and thermal equilibrium [32].

Several reference-environment models have been proposed [34]:

- Natural-environment-subsystem models: the temperature and pressure of this reference environment are taken to be 25°C and 1 atm. The chemical composition is taken to consist of air saturated with water vapor in equilibrium with condensed phases (Water, Gypsum and Limestone). The reference environment for this model is shown in tab. 1.1.
- Reference-substance models: "reference substance" is selected for every chemical element and assigned zero exergy.
- Equilibrium and constrained-equilibrium models: all the materials present in the atmosphere, oceans and a layer of the crust of the earth are pooled together and an equilibrium composition is calculated for a given temperature.
- Process-dependent models: considers only the components of the considered process, which the model is dependent of, at temperature and pressure of the natural environment.

Table 1.1: Natural-environment-subsystem model [34]

Reference environment		
Temperature		25 °C = 298.15 K
Pressure		1 atm
Composition	***Air Constituents***	***Mole fraction***
	N_2	0,7567
	O_2	0,2035
	H_2O	0,0303
	Ar	0,0091
	CO_2	0,0003
	H_2	0,0001

Exergy components

The total exergy of a system E can be divided into four components (in the absence of nuclear, magnetic, electrical, and surface tension effects):

- Physical exergy E^{PH}
- Kinetic exergy E^{KN}
- Potential exergy E^{PT}
- Chemical exergy E^{CH}

The following equation shows the balance:

$$E = E^{PH} + E^{KN} + E^{PT} + E^{CH} \qquad (1.1)$$

Then, if we work with it on a unit-of-mass or molar basis, the eq. (1.1) becomes:

$$e = e^{PH} + e^{KN} + e^{PT} + e^{CH} \tag{1.2}$$

The kinetic and potential energies of a system are fully convertible to work, so the kinetic and the potential exergies will be:

$$\begin{aligned} e^{KN} &= \frac{1}{2}V^2 \\ e^{PT} &= gz \end{aligned} \tag{1.3}$$

Where V is the velocity and z denotes the elevation relating to the coordinates in the environment.

Physical exergy is equal to "*the maximum amount of work obtainable when the stream of substance is brought from its initial state to the environmental state defined by temperature and pressure, by physical processes involving only thermal interaction with the environment*" [33].

Physical exergy, for a closed system, is given by the following:

$$E^{PH} = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) \tag{1.4}$$

where U, V, and S denote, respectively, the internal energy, volume, and entropy of the system at the specified state, whereas U_0, V_0, S_0 refer to the restricted dead state.

In addition, the physical exergy can be expressed by means of a unit-of-mass or molar basis:

$$e^{PH} = (u - u_0) + p_0(v - v_0) - T_0(s - s_0) \tag{1.5}$$

By referring to chemical exergy, it is defined as "*the maximum amount of work obtainable when the substance under consideration is brought from the environmental state to dead state by processes involving heat transfer and exchange of substances only with the environment"* [33].

As a consequence of the definition of the chemical exergy, the substances comprising the system must be referred to the properties of a suitably selected set of environmental substances [32]. Standard chemical exergy is referred to standard values of environmental temperature and pressure according to the reference environment. Moreover, reference substances with standard concentrations, which reflect as closely as possible the chemical real conditions of the natural environment, have to be set.

Once the reference-environment is selected, the chemical exergy can be evaluated as follow:

$$\bar{e}^{CH} = \sum_{i=1}^{n} \left(\mu_{i,0} - \mu_{i,00} \right) x_i \tag{1.6}$$

Where $\bar{e}^{CH}$ is the standard chemical exergy of component i, (kJ/kmol), $\mu_{i,0}$ is the chemical potential of component i in the mixture at the restricted dead state (kJ/kmol), $\mu_{i,00}$ is the chemical potential of component i at the dead state (kJ/kmol) and x_i is mole fraction of component i.

<u>Calculation</u>

With reference to fig. 1.5 , the general expression for an open system ‘exergy balance’, can be derived applying the concepts of energy and entropy. Eq. (1.7). illustrates the balance.

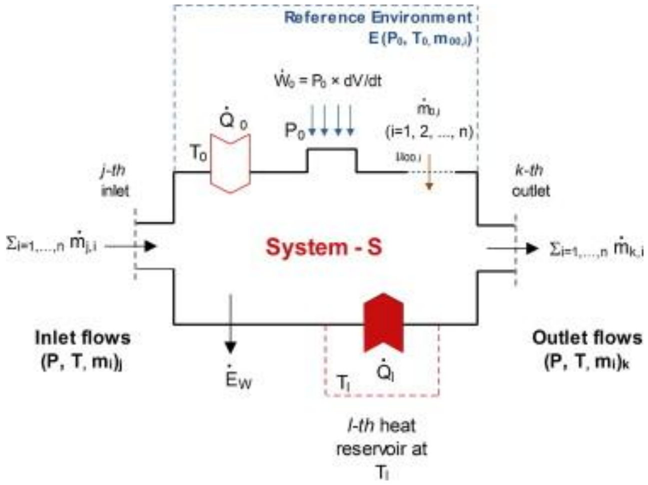

Figure 1.5: Control volume for exergy balance [1].

$$\frac{dE}{dt} = \sum_{i=1}^{p} (\dot{E}_Q)_i - \dot{E}_W + \sum_{j=1}^{q} (\dot{m} \cdot e_M)_j - \sum_{k=1}^{r} (\dot{m} \cdot e_M)_k - \dot{E}_{des} \tag{1.7}$$

where:

$$\dot{E}_Q = \dot{Q} \cdot \left(1 - \frac{T_0}{T} \right) \tag{1.8}$$

$$\dot{E}_W = \dot{W} - P_0 \frac{dV}{dt} \tag{1.9}$$

and:

$$\begin{aligned} e_M &= g(z_1 - z_2) + \frac{1}{2}\left(V_1^2 - V_0^2\right) + (u_1 - u_0) + P_0(v_1 - v_0) + \\ &- T_0(s_1 - s_0) + \frac{1}{MM_{mix}} \sum_{i=1}^{n} \left(\mu_{i,0} - \mu_{i,00}\right) x_i \end{aligned} \tag{1.10}$$

The latter eq. (1.10), expresses the specific exergy of a stream of matter consisting of n components, showing respectively the potential energy, the kinetic energy, the physical exergy and the chemical exergy.

Additional terms corresponding to the exergy content of nuclear energy of the material or to the exergy content of a flux of solar radiation may appear in eq. (1.10) [1].

The term $\dot{E}_{des}$ is a virtual term introduced in order to close the balance and does not correspond to any physical flux.

Exergy: advantages and drawbacks

To sum up, exergy has the following advantages [1]:

- Exergy measures both material and energy flows into comparable terms based on the capacity of generating mechanical work as a useful effect.
- Exergy identifies the thermodynamic losses in a process by means of the exergy destruction term.

Furthermore, in respect to energy, exergy has the advantages reported in tab. 1.2.

Table 1.2: Comparison between Energy and Exergy [34]

Energy	Exergy
Dependent on properties of only a matter or energy flow, and independent of environment properties.	Dependent on properties of both a matter or energy flow and the environment.
Has values different from zero when in equilibrium with the environment.	Equal to zero when in the dead state by virtue of being in complete equilibrium with the environment.
Conserved for all processes.	Conserved for reversible processes and not conserved for real processes.

Can be neither destroyed nor produced.	Can be neither destroyed nor produced in a reversible process, but is always destroyed (consumed) in an irreversible process.
Appears in many forms and is measured in that form.	Appears in many forms and is measured on the basis of work or ability to produce work.
A measure of quantity only.	A measure of quantity and quality.

For these reasons, exergy is a powerful tool capable of describing the flows of resources both within biophysical systems and industrial processes.

However, exergy can only take into account flows of resources that have a real exergy content. Indeed, many things we value, thermodynamics do not. In order to link economics and thermodynamics, as Valero argued [28], a drawback of exergy is in the fact that all the things we use every day have no exergy content from thermodynamic point of view.

A possible way is offered by new theories concerning the embodied energy. Embodied energy is the amount of energy units required to produce a given product. The concept of embodied energy comes from the 1970s and it was developed during the global energy crisis. Nevertheless, the drawbacks of the energy have already been discussed and some authors as Valero and Szargut assigned the concept of embodied energy to the exergy. Indeed, the exergetic cost or the cumulative exergy consumption refer to the same concepts of embodied exergy.

The concept of embodied exergy is a thermodynamic tool that may represents the answer to the questions raised by Industrial Ecology in order to merge economic and ecological dimension and quantifying the flows of materials, energy and goods and services within the biophysical sphere and the techno – sphere.

In the following chapters the concept of embodied exergy will be explained and developed and finally applied to trace the flows of resources between human activities and environment.

Applying exergy to macro-systems

Exergy analysis has mostly been applied industrial systems and processes, but its application can be extended to macro-systems, such as regional, national and global energy and material conversions [34].

Analyses of regional and national energy systems provide information concerning how effectively a society uses natural resources and seeks to balance economic aspects and efficiency.

In order to achieve the goal of a more equitable distribution of resources, can be fundamental the assessment and the comparison of various societies throughout the world. However, traditionally, natural resources are divided into energy and other resources and they are measured in different units. Exergy allows to assess these resources with one unifying measure.

In this work, exergy will be used in this perspective, through the application of the exergy analysis at macro-system level such as a country.

2. The concept of Embodied Energy and Exergy

2.1 Introduction

The concept of Embodied Energy refers to the sum of the direct and indirect energy, required by a target product, during its entire life cycle or to a defined point of the life cycle.

Direct energy requirements are defined as the sum of all energy contributions that are directly used in the provision of the target product (for instance electricity, natural gas, gasoline, etc).

Indirect energy requirements refer to the sum of all energy contributions that have been employed for producing the goods and services required by the target product over its life cycle.

The measurement of direct and indirect energy requirements allows a global and comprehensive view of all the cumulative energy requirements aimed at providing the target product.

The concept of "embodied energy" can be also adapted to exergy. In this way, it is possible to give a different weight to various forms of energy, enabling to measure the "quality" of energy rather than just the quantity.

In order to determine embodied energy or exergy in goods and services, a temporal domain and a spatial boundary have to be defined. By considering the entire life cycle of the target product, including every phase as the temporal domain, it is possible to evaluate the real impact of that product from 'cradle to grave'. The implementation of the standards required by the Life Cycle Assessment (LCA) methodology can help in this direction. The issue, relating to embodied energy or exergy analysis, is defining a spatial boundary that allows to consider the highest number of systems and infrastructures involved in the production of the target product. Obviously, if the control volume is larger, the accuracy will be increased because of the growing number of energy contributions that are taken into account. In this perspective, attempts to extend the control volume to ecological systems and human systems were made.

However, considering all systems and infrastructures is still not enough in a perspective of sustainable growth: the factors of production, such as capital and human labor, involved in the life cycle of the target product have to be checked and included into accounting.

In conclusion, the analysis of the embodied energy or exergy, in a well-posed LCA, provides a tool capable of giving information about goods or services that have an energy-intensive production chain, and evaluating and identifying the major losses in industrial processes.

2.2 Embodied Energy and Exergy in literature

During the energy crisis in the early 70s, the interest in the energy analysis strongly increased both for the growing energy prices and for a new perspective of the effects of the energy use on the environment. This new awareness of the negative aftermath caused by the intensive use of fossil fuels, changed the focus on the computation of the indirect energy requirements instead of the direct ones.

Several studies about the calculation of indirect energy requirements of a product of a specific economy were implemented in these years.

For instance, Chapman estimated the embodied energy or the energy cost of copper and aluminum [35] and calculated energy cost of fuels [36].

Over the same period, first studies about the energy cost of every good and service were introduced by Bullard [37] referring to Hereenden and Tanaka studies [38] on the energy cost of living for households in the U.S. economy.

Bullard and Hereenden started by the problem of quantifying the energy cost of goods and services for saving energy through the substitution of the products that required high energy use [39]. The concept introduced by Bullard and Hereenden is that the energy dissipated by a sector of an economy is passed on as embodied in a product of this sector. Applying this concept to every sector the following framework is set up: primary energy is extracted from the earth, is processed by the economy, and ultimately gravitates to final demand (personal and government consumption and exports).

Almost simultaneously, Wright estimated the energy cost of goods and services with a similar approach [40].

A few years later Costanza and Hereenden tried to find interrelationships between energy cost and economic cost of goods and services seeking to define an “Embodied Energy Theory of Value” [41].

After these years the concept of “embodied cost” was extended to other environmental indicators such as materials, pollutant emissions, land use and other parameters.

Recently, most of the studies about embodied energy are linked to the concept of sustainable buildings. Several examples related to life cycle energy analysis of buildings [42] and life cycle energy use in buildings [43] are available in literature.

Nevertheless the concept of embodied energy neglects the quality of different energy forms. Concepts about energy quality evolved over the decades from the early 1970s. Through the decades Odum understood that all forms of energy do not have the same ability to work and that “quality corrections” were necessary if one were to compare the different forms with respect to their differential ability to do work [44]. By combining human and natural systems and the concept of embodied energy, Odum defined a novel concept able to express the energy quality of the embodied resource flows in products, called Emergy.

Another way to develop the idea of the energy quality is exergy. In thermodynamic analysis the second law may be used explicitly by means of entropy generation and exergy [45].

Methods based on exergy analysis in a life cycle perspective are a step forward because they comply with the first and the second laws of thermodynamics.

For instance, methods such as Industrial Cumulative Exergy Consumption (ICEC) analysis [46] and Exergetic LCA [47] can capture the difference in terms of quality of the energy flows and materials that occur during the entire life cycle of a product.

The “exergy cost” concept was proposed by Valero, who has introduced the Exergy Cost Theory (ECT). ECT links thermodynamics and economics and postulates that the process of exergy cost formation of products runs parallel to the continuous and inexorable process of energy degradation of resources.

Among others, the Extended Exergy Accounting (EEA) developed by Sciubba, aims at determining the embodied exergy in the production of a good or service, including the effects of externalities on exergy consumption, such as human labor, capital expenditures and environmental costs (pollutant emissions).

Common terminology for Embodied Exergy concept

Several terms are commonly used to indicate the concept of embodied exergy. In literature, instead of embodied exergy, it can be found:

- Exergy cost
- Exergetic cost
- Cumulative exergy consumption
- Cumulative exergy content
- Primary exergy consumption
- Primary exergy requirement

For the sake of simplicity, in this work the concept of exergy cost will be used, among others, in order to refer to the exergetic external resources that have to be supplied to the overall system to produce the target product.

2.3 Life Cycle Assessment

The concept of embodied exergy expresses itself in the accounting of the environmental burdens linked to the life cycle or until a defined point of the life cycle of goods and services.

Life Cycle Assessment (LCA) is the analysis of all environmental burdens connected with the production of a good or service that have to be assessed back to raw materials and down to waste removal [48].

The analysis refers to direct and indirect environmental ‘loadings’ and ‘impacts’ associated with a process [49]. The loadings are, for instance, energy and material used and waste released into the environment [50]. These loadings can be measured quantitatively. The impacts concerns the consequences of material extraction and waste releases on the environment. Sometimes the impacts are considered qualitatively [51].

The assessment includes the entire life cycle of the product or activity, encompassing extracting and processing raw materials, manufacturing, distribution, use, re-use, maintenance, recycling, final disposal and all the transportation involved.

According to the Nordic Guidelines of Life Cycle Assessment [52], the general application areas of LCA are both in private and public sector.

The objectives achieved by the application of the LCA in a private sector perspective are:

- Identify processes, ingredients and systems that are the major contributors to environmental impacts
- Compare different options within a specific process with the objective of minimizing environmental impacts
- Provide guidance in long term strategic planning concerning trends in product design and materials
- Evaluate resource effects associated with particular products, including new products
- Help to train product designers in the use of environmentally sound product materials and
- Compare functionally equivalent products

In comparison, general applications in public sectors are:

- Help to develop long-term policy regarding overall material use, resource conservation and reduction of environmental impacts and risks posed by material and processes throughout the product life-cycle
- Evaluate resource effects associated with source reduction and alternative waste management techniques
- Provide information to the public about the resources characteristics of products and materials
- Identify gaps in knowledge and research priorities
- Supply information needed for legislation or regulatory policy that restricts use of product materials

- Help to evaluate and differentiate among the products for ecolabelling programmes

Therefore, in the private sector LCA is used to support product development and marketing decision and enhance the credibility of the company's environmental policy. Conversely public LCA studies are used to support environmental policies, regulation and legislation, develop criteria for environmental taxes or ecolabelling programmes and provide information to the suppliers [53].

2.3.1 State of the art and evolution

Life cycle assessment (LCA) originated in the early 1970s when the issues related to energy efficiency of systems and the consumption of raw materials were becoming more and more important. In the 1969 Coca Cola Company started to study the environmental burdens related to beverage containers. In the wake of Americans, Ian Boustead [54] calculated the energy requirement for various types of beverage containers, in 1972. Over the next few years, Boustead's methodology was improved and expanded to a variety of materials.

During 1970s and 1980s, several studies and methodologies were consolidated, but every study was different from each other.

Until the 1990s, there was not a common theoretical framework for this analysis. Subsequently the Society of Environmental Toxicology and Chemistry (SETAC) started to define a formal tool for LCA in order to:

- provide a picture as complete as possible of the interactions of an activity with the environment
- contribute to the understanding of the overall and interdependent nature of the environmental consequences of human activities;
- and to provide decision-makers with information which defines the environmental effects of these activities and identifies opportunities for environmental improvements.

Since 1994, after the SETAC commitment aimed to develop the methodology, the International Organization for Standardization (ISO) started to handle the standardization of the methodology, publishing the standards in the 14040 series [55].

Actually, LCA methods are still developing and improving in consequence of the diffusion of software and database specifically designed to perform a LCA analysis.

2.3.2 Methodology of LCA

Implementing Life Cycle Assessment requires four steps [51]:

1. Goal definition and scoping

2. Inventory analysis
3. Impact assessment
4. Improvement assessment

In the first step, the objective of the analysis is stated, assumptions, strategies and procedures for data collection are established. Moreover, system boundaries are established and a functional unit is set [56].

Inventory analysis aims to quantify inputs and outputs that cross the system burdens previously defined. Energy and raw materials, products and co-products and waste that participate to the life cycle of a product are considered and collected in this phase.

In the impact assessment the results of the inventory analysis are translated into potential environmental impacts. The potential environmental impacts are usually resource depletion, human health impacts and ecological impacts [53].

Improvement assessment is the last component of the LCA and it examines the different options that can be undertaken in order to reduce environmental impacts.

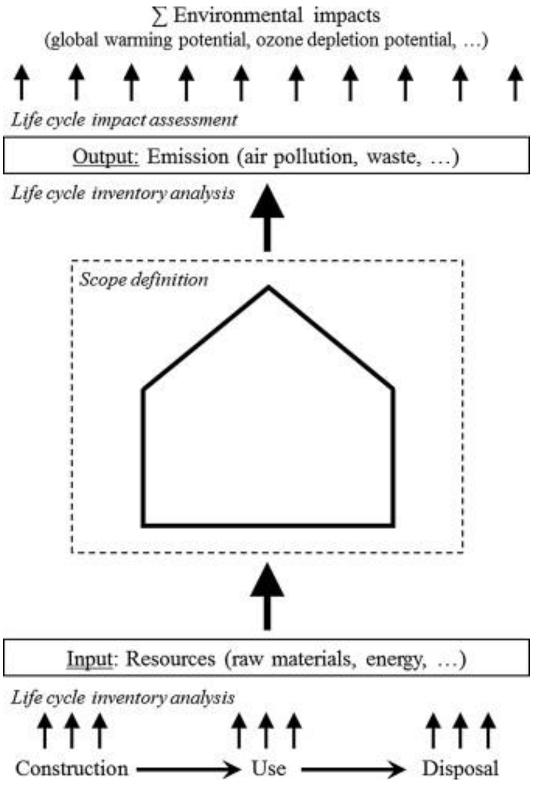

Figure 2.1: Life cycle assessment methodology of nearly zero-energy buildings [57].

2.3.3 Setting functional unit and system boundary

LCA is a tool in need of improvement. Indeed LCA suffers from variety of problems in every phase of its methodology [58].

In the first phase, ‘Goal definition and scoping’, is required to set a functional unit and define the boundary. These assumptions are always different and depend on the considered product.

The choice of the functional unit has to be in agreement with the scope of the LCA. Functional unit is used to compare different kinds of products which have the same functions. For instance, a LCA study on traction batteries [59] shows the influence of different functional units that can be defined - impacts per km, impacts per kWh, impacts per kg of battery etc. - in order to compare different types of batteries. Problems related to the choice of the functional unit can arise when (1) assigning functional units to multiple functions, (2) carrying out strict, functionally equivalent comparisons, and (3) when handling non-quantifiable or difficult-to-quantify functions [58, 60]. As stated, the functional unit have to be chosen in agreement with the aim of the analysis, enabling the measurement of the performance of the functional output of the product system (ISO 14040:1997).

In the first phase, another important problem is how to define the system boundary. The system boundary must be specified in many dimensions [61]:

- boundaries between the technological system and nature
- geographical area
- time horizon
- production of capital goods
- boundaries between the life cycle of the studied product and related life cycles of other products.

To address the boundary selection problem, ISO 14040:2006 standards recommend that the decision to select “elements of the physical system to be modeled” be based on: the goal and scope of the study, the application and audience, assumptions, constraints, and some ‘cutoff criteria’ that is “clearly understood and described”. These standards are often subject to criticism due to the subjective cutoff criteria, previously mentioned, that can introduce a truncation error. The efforts have been made to expand the boundary as much as possible. In this direction, IO LCA based approaches are preferred compared to process based analysis. Therefore, IO LCA-based approaches are a more comprehensive and faster way of selecting boundaries [58]. However, IO LCA methods suffer from other problems and errors that will be explained later.

2.3.4 Future development: Sustainable Life Cycle Analysis

Future developments in the LCA concern the possibility to perform an analysis over the life cycle of a product considering the three dimensions of the sustainability.

Life cycle sustainability assessment (LCSA) refers to the evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle [62].

LCSA is a tool that combines the Environmental Life Cycle Assessment (ELCA), the Life Cycle Costing (LCC) and the Social Life Cycle Assessment (SLCA).

Environmental LCA refers to the basic analysis previously described. ELCA aims at assessing the environmental aspects associated with a product (good or service) during the over life cycle.

Life Cycle Costing is the oldest technique among the others cited. LCC attributes every direct cost required by the life cycle of a product ‘from cradle to grave’.

Social Life Cycle Assessment is a technique to assess the social and economic impacts resulting from the life cycle of a product [63]. In this context a particular social aspect that can be part of the analysis is the labor force ‘embodied’ in the life cycle of a product as shown in fig. 2.2.

Implementing the LCSA demonstrates the efforts made by the scientific community to merge the three dimensions of the sustainability to have a tool capable of performing an optimization observing the concept of a sustainable growth.

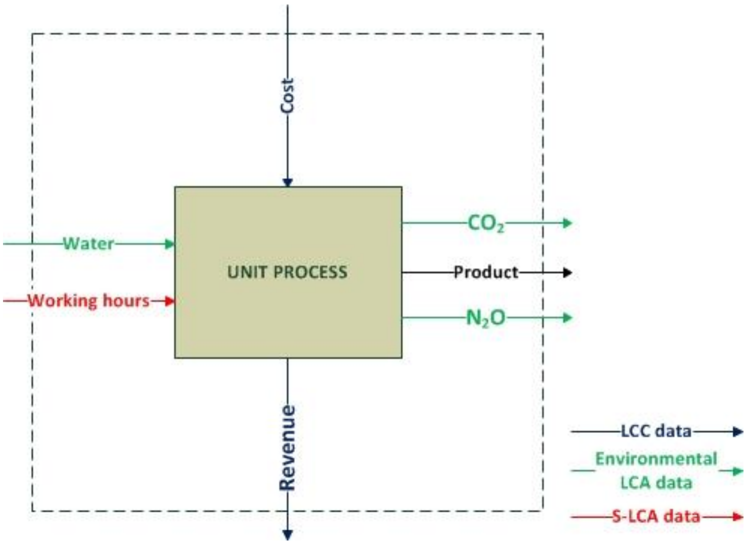

Figure 2.2 Example of Life Cycle Sustainable Assessment inventory data for unit process and organization levels [64].

2.4 Embodied Energy and Exergy in LCA perspective

In a LCA perspective, once the system boundary for the life cycle of a product is defined, the inventory of the resources which pass through it, can be various: emissions to air, fossil fuels, energy use, raw materials, minerals, land use, water use etc. The accounting of these resources is certainly important to evaluate the possible future scenarios in a sustainable perspective. However, in order to carry out a rigorous analysis, it is necessary to implement a biophysical method that complies with the basic scientific laws such as the first law of thermodynamics, which implies mass and energy conservation, and the second law concerning the degradation of the energy quality [65].

In this context energy and exergy are numeraires that allow to take into account a huge number of resources compared to other resource accounting methods.

This paragraph aims at providing an overview of the most commonly used methods energy-based and exergy-based that seek to quantify the consumption of the resources over the life cycle of a product.

Methods will be explained below by means of their definition, objectives, methodologies and their limitations and benefits.

2.4.1 Net Energy Analysis

The concept of Net Energy Analysis or Cumulative Energy Consumption (CEnC) refers to the total energy required to provide a good or service, considering direct and indirect contributions among the production chain [66]. In the early 1970s these studies were the first concerning a LCA view and, usually, they considered only non-renewable fossil fuels in the accounting.

The objectives of these analysis are the calculation of the total primary energy intensity of products (the energy cost of those products) and the Energy Return on Investment (EROI) that is the ratio of the energy delivered by a process, or the usable acquired energy, to the energy used directly and indirectly in that process [67]:

$$\mathrm{EROI} = \frac{\text{fuel value of products}}{\text{cumulative processing energy}} \tag{2.1}$$

The energy cost of any economic activity or commodity can be measured by either two methods of energy cost accounting: process analysis or Input – Output (IO) analysis.

Despite the popularity of this methodology, Net Energy Analysis suffers from problems such as the non-compliance with the second law of thermodynamics and the inability to include various forms of resources.

However this methodology was, and still is an innovative analysis, especially referring to the methods of energy cost accounting implemented in this analysis.

2.4.2 Emergy analysis

Emergy is the ‘available energy of one kind (for instance solar energy) required directly and indirectly to make a product or service’ [68].

The term ‘‘Emergy’’ refers to the ‘energy memory’ of every good and service and was proposed to eliminate the controversy between embodied energy and exergy by Odum [69].

In contrast to other methods, Emergy has its own unit of measureament: the emjoule or the solar emjoule, in order to take back every kind of resource consumption in one kind of energy (for example solar energy).

As the exergy, Emergy is able to account different and various forms of resources and it is able to consider the different quality of the energy flows [70], applying the concept of transformity. or transformation ratio, which is defined as “the solar Emergy required to make one Joule of a service or product”. For instance, Emergy analysis states that 1 J of biofuel is equivalent to 10^6 J of sunlight. Other detailed calculations about transformities are available in literature.

The technique is based on four rules [71]:

1. All the Emergy related to a process is assigned to the processes' output.
2. By-products from a process have the total Emergy assigned to each pathway.
3. When a pathway splits, the Emergy is assigned to each 'leg' of the split based on its percent of the total energy flow on the pathway.
4. Emergy cannot be counted twice within a system: (a) Emergy in feedbacks cannot be double counted: (b) by-products, when reunited, cannot be added to equal a sum greater than the source Emergy from which they were derived

Emergy is also able to take into account economic inputs and human resources. Indeed this calculation is carried out by means of the information of the Emergy consumption in the society, defining an Emergy/money ratio [72].

As stated in [70], as each new idea, Emergy is widely criticized. As the other methods, Emergy analysis suffers from uncertainties, especially in the quantification of the transformities; moreover Emergy analysis has allocation problems mostly related to co-products. In any case, Emergy analysis appears as the first attempt to unify the processes that occur in ecosystems and human activities.

2.4.3 Cumulative Exergy Consumption Analysis

Cumulative Exergy Consumption (CExC) Analysis has been proposed by Szargut and Morris (1986). It is similar to net energy analysis, but, instead of energy, it uses the exergy as numeraire.

CExC expands the analysis boundary by considering all industrial processes needed to convert natural resources into the desired industrial goods or services [73].

The employment of the exergy as numeraire allows to take into account not only energy flows that cross the system boundary, but also all types of material. In addition exergy can measure some environmental impact such as the emissions.

The CExC analysis uses the method of the accumulation of the primary exergy during the manufacture of a good or service, thus to a defined point in the life cycle analysis [74].

CExC can be developed in different ways [73]:

- Industrial Cumulative Exergy Consumption (ICExC)
- Ecological Cumulative Exergy Consumption (ECExC)

ICExC analysis considers only the exergy content of the natural resource inputs needed for a process. This methodology does not include the role of nature.

ECExC considers also exergy consumed by ecological processes to produce the raw materials, dissipate the emissions, and functioning of industrial processes. The latter, as the definition stated, is very close to the Emergy concept, trying to expand the boundary over the ecosystem processes. Furthermore, the method used to carry out the analysis is very similar. Indeed, ECExC uses an analogous concept of emergy transformity, called Ecological Cumulative Degree of Perfection (ECDP), in order to connect exergy and embodied exergy of products. Moreover, human economic activities are also taken into account by means of an ECExC/money ratio [75].

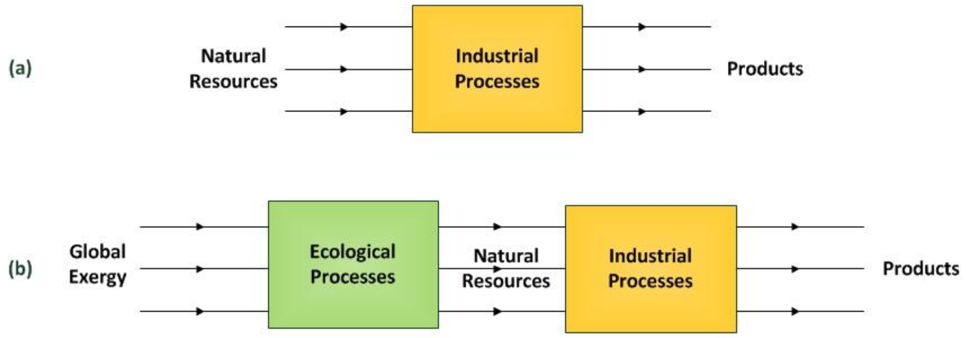

Figure 2.3: (a) Industrial Cumulative Exergy Consumption and (b) Ecological Cumulative Exergy Consumption [73].

Figure 2.3 shows the different system boundaries of the two methodologies.

Even if ICExC and ECExC have the advantage of using exergy as numeraire, they suffer from problems related to their nature. Indeed, ICExC is not able to have a wide boundary that includes the processes of ecosystems and ECExC, due to its similarity with the allocation system used in Emergy analysis, is affected by several uncertainties caused by the lack of data for most of the processes that occur within ecological systems.

However, in this method the exergy destruction associated with the disposal of the product and the influence of recycling which cause a change in the exergy destruction are not taken into account [74].

2.4.4 Exergetic Life Cycle Assessment

Exergetic Life Cycle Assessment (ELCA) implemented by Cornelissen, is an extension of LCA analysis aimed at evaluating the irreversibility that may occur during the life cycle of a product and at performing an analysis to assess and evaluate the degree of thermodynamic perfection of the production processes for the whole process chain [76].

ELCA combines Cumulative Exergy Consumption and LCA by also considering exergy consumption in the demand chain [77].

Moreover, in order to include environmental impacts due to emissions, an extension to the method of ELCA, the Zero-ELCA, was presented in which emissions are translated in terms of exergy.

The methodology is similar to LCA: the goal definition and scoping of the LCA and ELCA are completely identical. The inventory analysis of the ELCA is more extensive. The impact analysis is limited to the determination of the exergy of the flows and the calculation of exergy destruction in different production processes.

The accumulation of all the exergetic flows and losses gives the life cycle irreversibility of the product.

An important step in this methodology was achieved with the definition of the Zero ELCA. Zero ELCA is a methodology able to give an amount of exergy for the abatement costs required by emissions. Through this method not only the depletion of the natural resources is taken into account but also the exergetic cost of the environmental externality [76].

2.4.5 Extended Exergy Accounting

Definition and fundamentals

Extendend Exergy Accounting (EEA) was coined in 1998 by Sciubba [78].

EEA adopts the standard exergy accounting method of CExC to embody into a product all the exergetic contributions incurred in its entire life cycle: extraction, refining, transportation, pre-processing, final processing, distribution and disposal activities are computed in terms of exergy consumption [79].

Unlike CExC, but similarly to ELCA as shown, EEA refers to the entire life cycle and not only to the manufacture of the product. Another fundamental difference between EEA and other methods is that EEA aims at solving the problem of the conversion of non-energetic expenditures, taking into account non-energetic externalities such as labor, capital and environmental remediation costs.

In order to assess the non-energetic externalities, EEA is based on the concept of Thermoeconomics (TE). TE can be considered as exergy-aided cost minimization. TE combines exergy analysis and economic principles to provide the system designer or operator with information not available through conventional energy analysis and economic evaluations, but crucial to the design and operation of a cost-effective system [80]**.** This 'exergy costing principle' is used to assign monetary values to all material and energy streams within a system [81].

However TE has two weak points. Firstly, it suffers from two separate quantifiers: exergy, to assess the efficiency of a process, and money, in order to evaluate the economic costs associated with that process [79]. Therefore, the assumption of a strictly monetary basis to consider energy flows and materials is influenced by market considerations [1]. Second, in consequence of the first weakness, the assessment of the environmental issues is difficult [79].

For these reasons, it could be more convenient to base the method on purely physical parameters. EEA expresses all the expenses by means of a single quantifier: the exergy.

The method

The choice of the control volume in the EEA is restricted by two orders of considerations [78]:

- The control volume has to be far enough from the process under consideration in order to evaluate the outputs from the control volume in a state of zero physical exergy.
- If the inputs include unrefined fossil fuels or minerals in as-mined conditions, the control volume must include the portion of the environment whence the original materials were extracted, in this way their initial (physical) exergetic value may be taken into account. As an alternative, an extended exergetic value for every input can be assigned, estimating an initial value on the basis of an approximate knowledge of the extraction – pre-treatment – transportation process.

For the time domain, EEA is similar to LCA: construction, production and decommissioning phases are taken into account. Two considerations can be made on the time domain: the time frame over which mineral ores or fossil fuels are exploited has to be defined because of the change in extended exergy accounting of the extraction processes in the course of time, and the possibility to expand the time domain to include the concept of biodegradability of a product. According to these two aspects the choice of the time domain should be taken referring to each case [82].

EEA computes in its accounting:

1. Exergy costs of materials and energy flows, considering renewable and non-renewable resources. The way to take into account these contributions is the same as CExC.
2. Exergy costs of externalities including labor, capital and environmental remediation costs (the latter is similar to the concept explained in Zero-ELCA analysis). The contribution of the externalities is expressed by means of primary exergy equivalents of the labor, capital and environmental cost contributions: E_L, E_K and E_O.

In analytical form [1]:

$$EE = CExC + E_{ext} \tag{2.2}$$

$$E_{ext} = E_L + E_K + E_O \tag{2.3}$$

And, considering the spatial and time domain:

$$EE = (CExC + E_{ext})_{const.} + (CExC + E_{ext})_{op.} + (CExC + E_{ext})_{dis.} \tag{2.4}$$

Where, every term in (2.4) can be expressed in the following way:

$$EE_{const.} = \int_{t_0}^{t_{const.}} (CExC + E_{ext})\, dt \tag{2.5}$$

EEA expresses all costs in congruent units (kJ/(kg of product), or kJ/(kJ of work)), so that these costs can be directly added:

$$eec_i = \frac{EE}{n_i} \tag{2.6}$$

In (2.6) n_i is the cumulative amount of the product i expressed with its functional unit.

In the equation (2.3) the sum of labor externality, capital externality and the costs associated with the environmental remediation, gives the total amount of exergy consumption related to the externalities.

Labor and Capital externalities, are defined through two econometric coefficients that are established according to two postulates [1]:

1. In any Society, a portion of the gross global influx of exergy resources is used to sustain the workers who generate Labor.
2. The amount of exergy required to generate the net monetary circulation within a society is proportional to the amount of exergy embodied into labor.

By referring to the assessment of the environmental impact, EEA includes in the exergetic cost of a product the environmental pollution avoidance cost, determined as the additional exergy consumption that is needed to bring the environmental discharges into a zero physical exergy level [83].

Advantages and possible future developments

EEA represents, substantially, an extension of the Cumulative Exergy Consumption because it allow the inclusion of the so-called non-energetic externalities into the exergy accounting such as the production factors. EEA is a step-forward in a Life Cycle Sustainable Assessment perspective. The inclusion of the externalities allows to evaluate the resource flows after being processed by human activities, performing an optimization of the systems that, for the first time includes the contributions of the social sphere.

However, some drawbacks have been raised in the EEA formulation. The major issues concern the extension of the CExC database and more accurate models to measure the exergy equivalent from labor and capital [1].

2.5 The role of Human Labor in embodied energy and exergy

Human labor is necessary to produce goods and services. Production is a work process that uses energy to transform materials into products.

However there are some service activities that seem to not require the direct processing of materials. This is true only if the focus is at micro-level scale. In a wide-economy approach all processes need indirect contributions of materials and energy in order to sustain two factors of production: labor and capital [84].

Nicholas Georgescu-Roegen [85] elaborates a model that describes production as a process able to transform materials and energy in goods and services by two agents of transformation: human labor and manufactured capital.

Human labor and capital cannot be avoided from the resource consumption required by the provision of a good or service because they are strictly interrelated to the production of products.

Recently more and more attempts have been made to include labor and capital externalities into account. Quantitative values for the environmental impacts of labor and capitals are needed to improve the accuracy and expand the decision making capabilities of life cycle analysis.

This paragraph will be focused on the review of some methods that include the assessment of labor environmental impact in the embodied energy and exergy accounting.

2.5.1 Inclusion of Labor in Net Energy Analysis

Since 1980 Costanza, a pioneer of the net energy analysis, sought to find an answer to the question: ‘Are conventional primary factors – capital, labor, natural resources and government services – free from indirect energy costs?’ [41].

To assess the importance of those primary factors, Costanza and Herendeen (1984) used an 87-sector input-output model of the US economy for 1963, 1967, and 1973, modified to include households and government as endogenous sectors in order to include the energy cost of labor and the energy cost of government expenditures and analyze their impact in terms of energy [86].

Costanza and Herendeen found that labor costs could not be neglected because of their large fraction of the expenditure related to each sector of the economy, in order to pay wages.

Costanza and Herendeen [87], conclude that in the case of calculating a static measure of total energy cost it seems appropriate to consider humans to be endogenous, that is to consider human labor as active part of the production process.

Table 2.1: Inclusion of Government and Household expenditures in the IO table [41].

<table>
<tr><th colspan="4">87-sector IO model of the US economy</th></tr>
<tr><th></th><th>Current Input - Output Sectors</th><th>Government</th><th>Households</th></tr>
<tr><td>Current Input - Output Sectors</td><td></td><td>Government purchases of goods and services</td><td>Personal consumption expenditures</td></tr>
<tr><td>Government</td><td>Indirect business taxes</td><td></td><td>Personal taxes</td></tr>
<tr><td>Households</td><td>Employee compensation</td><td>Government salaries</td><td></td></tr>
</table>

2.5.2 Inclusion of Labor in Emergy Analysis

The Emergy method is able to include in the evaluation the emergy supporting human work and services.

By applying the concept of transformity, useful to differentiate energy forms, Emergy approach defines an emergy per unit of labor as the amount of emergy supporting one unit of labor directly supplied to a process. Workers, in order to support processes, have to invest indirectly the emergy gained by food, transport, training etc. This emergy intensity is generally expressed as emergy per time (seJ/year, seJ/h), but emergy per money earned (seJ/$) is also used [44]. Sometimes the emergy in human services is estimated as the dollar costs of human services multiplied by the average ratio of emergy to money for the economy where the process is located. The emergy to money ratio for an economy is determined by dividing the total emergy used in an economy by the total circulation of money in the economy estimated by Gross Domestic Product [88].

However in other emergetic analysis, (as for instance [89] and [90]), human work is calculated using calories required by human metabolism per hour, neglecting other services associated with human sustainment.

2.5.3 Szargut's point of view on the inclusion of human work

Szargut, one of the pioneer of the Cumulative Exergy Consumption method, dealt with the ecological cost of human labor [91]. He stated that the human work must fulfill the following criterion:

"The sum of the cumulative indices of energy or exergy consumption of all the final useful products used by the society should equal to the total consumption of primary energy or exergy, taken from the natural sources."

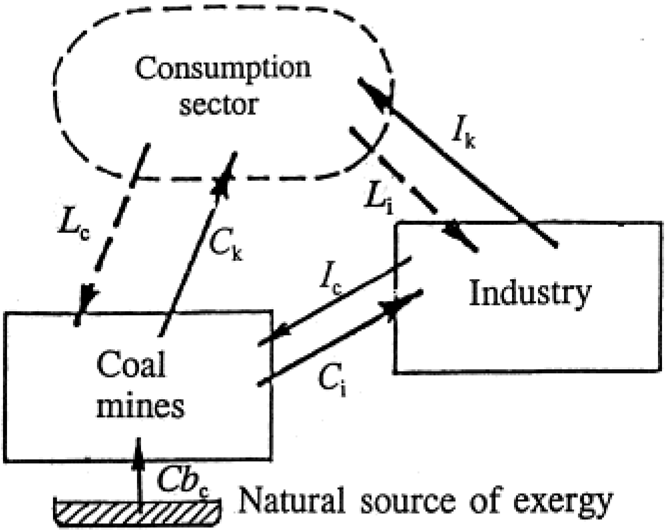

Figure 2.4: Scheme of the simplified system [91].

Referring to fig. 2.4, which represents a simplified scheme of interactions between environment and human activities, Szargut sets up these system of equations:

$$b_c^* = b_c + \frac{I_c}{C}\rho_i + l_c r \tag{2.7}$$

$$b_i^* = \frac{C_i}{I} b_c^* + l_i r \tag{2.8}$$

Where:

- b^* is the specific cumulative consumption of primary exergy
- b_c is the specific exergy of coal
- b_i is the specific exergy of industries
- I is amount of useful industrial products
- I_c is the consumption of industrial products in coal mines
- I_k is the consumption of industrial products in consumption sector
- C is the production of the coal
- C_i is the part of produced coal used in industrial processes
- C_k is the part of produced coal consumed immediately
- ρ_i is the specific ecological cost of the i product
- l_c , l_i are specific consumption of human production work in coal mines and industry
- r the mean ecological cost of human work per time unit

From (2.8) it results:

$$b_c^* = \frac{b_c + \left[l_c + \left(I_c/C\right)l_i\right]r}{1-\left(I_c/I\right)\left(C_i/C\right)} \tag{2.9}$$

And the total consumption of primary exergy can be expressed as:

$$b_i^* I_k + b_c^* C_k = b_i^*\left(I - I_c\right) + b_c^*\left(C - C_i\right) = Cb_c + \left(l_c C + l_i I\right)r \tag{2.10}$$

Szargut states that the total balance (2.10) of exergy consumption is closed only if the cumulative consumption of primary exergy concerning the human production labor is omitted in the set of equations. In this way he demonstrates that the ecological cost of human work cannot be introduced into the set of input–output equations in order to avoid double accounting.

2.5.4 Human Labor in Extended Exergy Accounting

One of the novelties of EEA is the computation of the exergy cost of the human labor. In other methods, such as thermoeconomics and net energy analysis, the labor is counted by a purely monetary basis. Sciubba's idea is based on Odum's emergetic approach in order to include the impact of the human work, as described in the previous paragraph.

EEA assigns an exergetic value to labor that is the amount of exergy resources consumed by each worker to sustain his living standards in the society [83].

Sciubba points out the importance of the accounting for human labor, stating that even if just the metabolic rate is taken into account, the results concerning the resource consumption in the life cycle of a product, change greatly because of the same order of magnitude as other production factors. Hence the exergy consumption caused by human work is not negligible.

In more detail, EEA theory assigns an equivalent exergetic value to labor, and in general, human services equal to a portion of the net primary exergy input on the Earth [92] as shown in fig. 2.5.

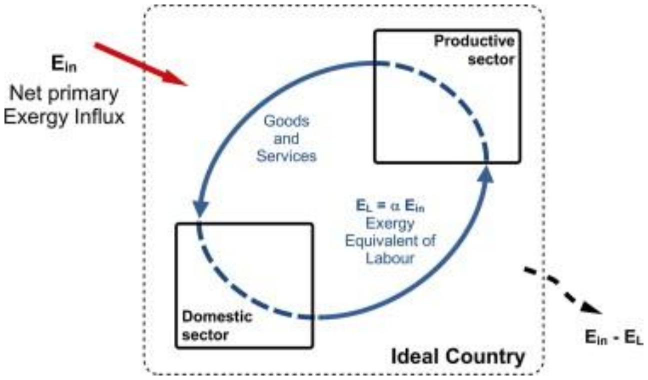

Figure 2.5: Exergy analysis of a macroscopic human society [1].

In mathematical terms:

$$EE_L = \alpha E_{in} \tag{2.11}$$

α is the econometric coefficient defined as [1]:

$$\alpha = \frac{f \cdot e_{surv} \cdot N_h}{E_{in}} \tag{2.12}$$

Where:

- e_{surv} represent the minimum exergy amount required for the metabolic survival of an individual
- N_h is the number of individuals in the population
- f is an amplification factor with respect to e_{surv}. This factor takes into account the different living standards in countries. Indeed it is based on the Human Development Index (HDI), adopted to distinguish countries in relation to life expectancy, health and education levels.

Through the amplification factor, EEA considers a certain amount of exergy consumption, which depends on the average living standards related to each country, higher than the basic metabolic rate in order to estimate the consumption of other goods and services, such as transport, education etc. , needed by workers to make available their labor force, enabling the production process of new products.

3. Methods for Exergy Cost Analysis

3.1 Introduction

The aim of this chapter is to explain the methods for Exergy (and Energy) Cost analysis. As stated previously, the embodied exergy or the exergy cost is the sum of direct and indirect exergy requirements needed by a process. Direct contributions comprise the exergy directly used in the main process. Indirect exergy, at first level, refers to the exergy contributions required by the goods and services involved in the main process. At second level, indirect exergy refers to all exergy contributions required by goods and services involved in the processes of the first level, and so forth.

Methods for calculating Exergy (and Energy) Cost were discussed by Treloar [93]:

- Process Analysis
- Input – Output Analysis
- Hybrid Analysis

Methods will be described referring to the mathematical model, benefits and drawbacks as shown below.

3.2 Process Analysis

3.2.1 Introduction

Process analysis requires to set a good or service, which is the object of study. The analysis aims at providing information referring to goods and services involved in the life cycle or to a defined point of the life cycle of the target product under consideration.

The target product receives exergy inputs at different stages. At the first level, it requires goods or services that have a certain amount of exergy embodied in their manufacture. In order to evaluate the exergy cost of those goods and services, which are involved in the life cycle of the target product, tracing back through each stage is necessary. Each stage requires typically smaller and smaller exergy inputs until reaching infinite steps and negligible inputs. The sum of exergy requirements of each stage determines the embodied exergy [37].

3.2.2 Example: Embodied Energy in a two-sectors economy applying Process Analysis

For illustration, in this section will be explained an example of a process analysis for a simplified economy.

For the sake of simplicity energy will be used instead of exergy because this example does not apply for evaluating energy quality.

The objective of this example is to determine direct and indirect energy required by the target product.

The assumptions made are:

- A closed economy that is self-sufficient, meaning that no imports are brought in and no exports are sent out.
- Two-sectors economy composed of an energy sector and one industrial sector.
- Fuels enter in the energy sector in the form of goods, since energy sector does not extract resources directly from the environment (for instance it is possible to imagine that the industrial sector contains Mining and Quarrying sector).

The data referring to the processes are illustrated in fig. 3.1.

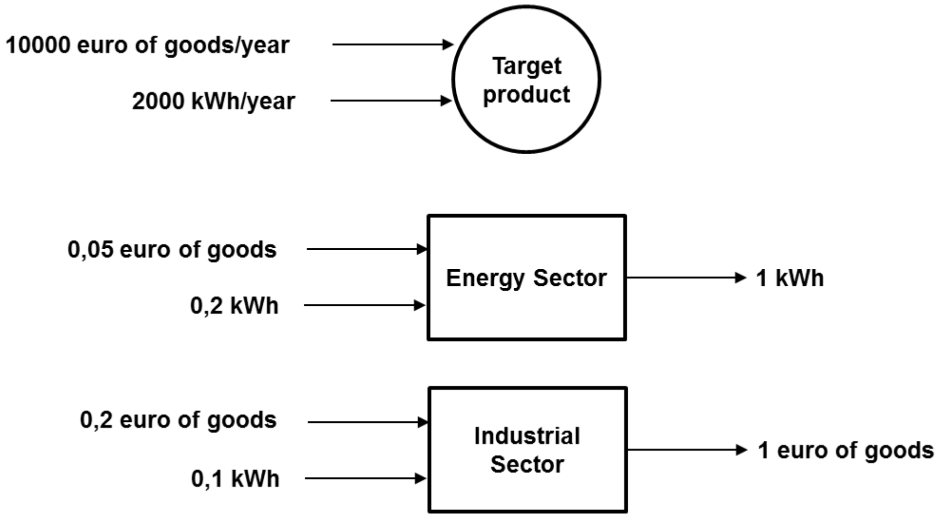

Figure 3.1: Process data related to example 3.2.2.

The direct energy requirements are already known from the data: the target product receives goods and energy directly from the economy. The data are referred to requirements in one year.

Other data refer to how the production works in each sector of the economy and what is needed as inputs in order to provide a specific demanded output.

In order to assess indirect contributions, which are hidden in the processes, process analysis is required.

Fig. 3.2 shows four stages in the process analysis in order to point out the indirect requirements for the target product in the economy under consideration. The figure shows also the typical ‘tree structure’ of the process analysis.

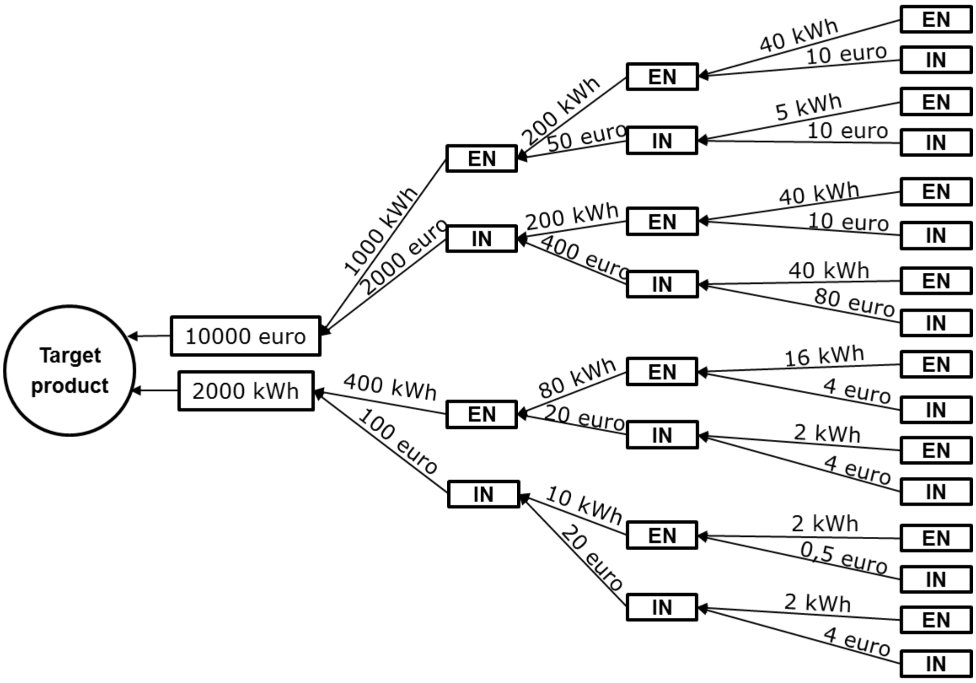

Figure 3.2: Process analysis in four stages. EN refers to energy sector, IN to industrial sector.

The steps in the fig. 3.2 are calculated as follow:

$$\begin{aligned} x_{EN\,(direct+indirect)} = {} & \underset{\text{direct requirements}}{f_{EN}} + \underbrace{a_{11}f_{EN}+a_{12}f_{IN}}_{\text{indirect requirements II stage}} + \underbrace{a_{11}(a_{11}f_{EN}+a_{12}f_{IN})+a_{12}(a_{21}f_{EN}+a_{22}f_{IN})}_{\text{indirect requirements III stage}} + \\ & + \underbrace{a_{11}\left[a_{11}(a_{11}f_{EN}+a_{12}f_{IN})+a_{12}(a_{21}f_{EN}+a_{22}f_{IN})\right]+a_{12}\left[a_{21}(a_{11}f_{EN}+a_{12}f_{IN})+a_{22}(a_{21}f_{EN}+a_{22}f_{IN})\right]}_{\text{indirect requirements IV stage}} \end{aligned} \tag{3.1}$$

The equation (3.1) shows just four stages of calculation, where:

- $x_{EN\,(direct+indirect)}$ is the sum of direct and indirect energy
- f_{EN} is the final direct supply of energy
- f_{IN} is the final direct supply of goods and services

- a_{11} is a technological coefficient of the energy sector: how much energy is required to produce a unit of energy; in this example, it is equal to 0,2 $\frac{\text{kWh}}{\text{kWh}}$.
- a_{12} is a technological coefficient of the industrial process: how much energy is required to produce a unit of goods; in this example, it is equal to 0,1 $\frac{\text{kWh}}{\text{euro}}$.
- a_{21} is a technological coefficient of the energy sector: how many goods are required to produce a unit of energy; in this example, it is equal to 0,05 $\frac{\text{euro}}{\text{kWh}}$.
- a_{22} is a technological coefficient of the industrial sector: how many goods are required to produce a unit of goods; in this example, it is equal to 0,2 $\frac{\text{euro}}{\text{euro}}$.

The stages that have been computed are just four. A large number of terms are never computed. The analysis is complete when the amount of energy required by other stages is believed to be negligible. Nevertheless diminishing the amount of energy required for each stage provide no guarantee that the sum of that single negligible contributions is also negligible [37].

The results can be represented by an area graph in fig. 3.3. The graph shows the decreasing contributions if more stages are added in the analysis.

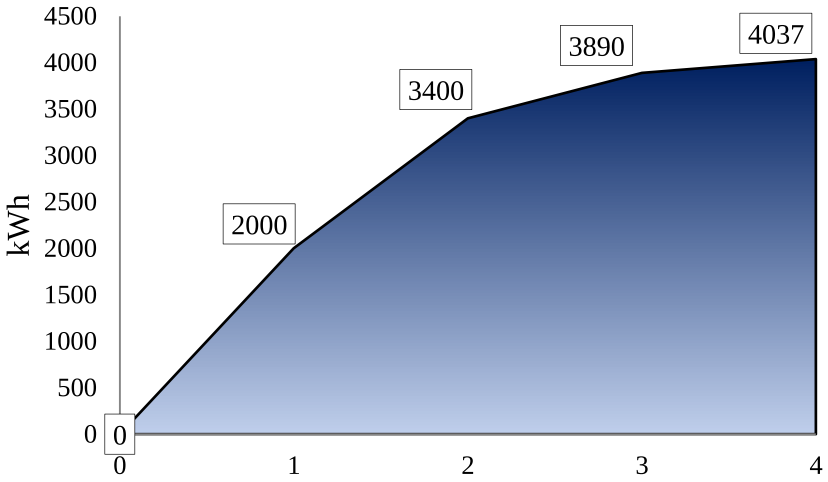

Figure 3.3: Cumulative Energy Consumption applying Process analysis.

3.2.3 Mathematical model

The mathematical model of a process analysis can be implemented by the use of vectors and matrices [94, 95].

It is possible to define the vector of the total direct plus indirect requirements of goods and services. Referring to the previous example the vector can be written as follow:

$$\mathbf{X} = \begin{bmatrix} x_{EN} \\ x_{IN} \end{bmatrix} \tag{3.2}$$

The direct requirements of goods and energy for the target product form the vector of the final demand:

$$\mathbf{f} = \begin{bmatrix} f_{EN} \\ f_{IN} \end{bmatrix} \tag{3.3}$$

The technological coefficients, specific to each process can be collected in a matrix, called matrix of technological coefficients:

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \tag{3.4}$$

Therefore, the mathematical model can be written as follow, as also suggested by the equation (3.1):

$$\mathbf{X = (I + A + AA + AAA + ...)\,f} \tag{3.5}$$

Where **I** is the identity matrix.

The eq. (3.5) shows the power series expansion, commonly used to interpret the Leontief inverse in Input – Output analysis (IOA). The i-th term in the expansion represents the required products in the i-th production stage. In the zero-th production layer, **f** represents the direct requirement for the target product. To produce **f** an input of **Af** is required into the first tier production layer. To produce **Af** an input of **A**(**Af**) is required in the second production stage, and so on through the infinite expansion [96].

The mathematical model can obviously be adapted to an economy larger than one limited to few sectors, replacing **X** and f in a $(n \times 1)$ vectors and **A** in a $(n \times n)$ matrix, where n is the number of the sectors.

3.2.4 Process Analysis: benefits and limitations

Process analysis requires several data on the production of the target product and other data referred to the second, the third and other inputs not truncated.

For data related to the industrial process, the information have to be obtained from the manufactures, and this can be usually a problem. For data about economic sectors and aggregated production sectors, the information have to be obtained from government or statistical institutions.

If data are accurate, process analysis is able to define the real flows of the resources required by the target product for each stage of the analysis.

In a real analysis some negligible branches of the tree are not computed in order to decrease the efforts for data acquisition. Nevertheless this technique introduces a undefined truncation error.

Advantages related to the process analysis [97] are shown below:

- results are detailed, process specific
- allows for specific product comparisons
- identifies areas for process improvements, weak point analysis
- provides for future product development assessments

On the other hand the disadvantages related to the process analysis [97] are:

- setting system boundary is subjective
- tend to be time intensive and costly
- difficult to apply to new process design
- use proprietary data
- cannot be replicated if confidential data are used
- uncertainty in data

3.3 Input – Output Analysis

3.3.1 Introduction

Input – Output Analysis (IOA) is the name of the analytical framework developed by Professor Wassily Leontief who was awarded the Nobel Prize for the development of the input - output method and for its application to considerable economic problems.

Input – Output tables (IOTs) are usually large tables of data that point out the interconnections between the sectors of the economy, households and government. The interconnections between these entities are made assuming that the output of an industry can be represented as an input of other industries. Indeed, IOA was born as an economic framework, able to trace the flows of money among the economy. The model is also awarded for having the ability to measure the total effect or impact of an increase in demand on employment or income and forecast the future developments of the economy in terms of efficiency and productivity growth [98].

IOA is still under development: extension of the input – output model has been made from environmental point of view with the so called environmentally extended IOT. It has been also extended to be part of an integrated framework of employment and social accounting metrics and efforts have been made to apply IOA at many geographic levels – local, regional, national, and even international [94].

In this paragraph IOA will be described starting from the history and the developments of these methodology during the years; moreover the mathematical model will be implemented and different types of IOTs will be explained. Finally the state of the art of this methodology and future possible improvements of the technique will be illustrated. Obviously the IOA framework will be explained from an environmental point of view in order to follow the aim of this thesis: applying the IOA as a method able to provide information about embodied exergy along the life cycle of goods and services.

3.3.2 Brief history

During the last two centuries economic science was developed with the application of mathematics, statistical methods and more recently, computer science, to the economic data to have a quantitative analysis of the economic phenomena. A new term was coined in order to define a new science that merged economics, mathematics and statistics: Econometrics. In 1930s when econometrics and its applications were consolidated, the attempts were aimed at finding a meeting point between qualitative economic methods based on observations and interviews and quantitative economic methods based on hypothesis, measurements and deductive conclusions. In this context Leontief’s work on multi-equation model of sectorial mesoeconomic relations was developing [99].

However is well know that an important contribution to IOA was made before Leontief’s work in 1904 by the Russian economist Dmitriev, who proposed a system of equations for the determination of full labor costs [100].

According to Stone, in the early 1920's, the Central Statistical Administration of the Soviet Union compiled a large body of data on material outputs and their uses, well-distributed in the form of an input-output table for 1923-24, as a basis for planning production [101]. Even if the Soviet Balance is very close to input-output rectangular tables, there is no evidence that it can be a reasonable approximation of Leontief’s work. Indeed, the 1926 Soviet Balance was a statistical table but did not use matrix algebra or coefficients [99]. Few years later the Soviet Balance, M. Barengol’ts developed technical coefficients relating intermediate expenditures in each branch to the total output of that branch, a procedure very close to Leontief’s approach [102].

The Soviet Balance was followed by some works on multi-sectoral issues in Western Europe and especially in Germany where W. Leontief worked on his Ph.D. thesis in Berlin: ‘The National Economy as a Circular Process’ [103] and where he, after completing his Ph.D., was in the Institute for World Economics in Kiel. However, this European work was not collected in a systematic way and did not pass the experimental stages [99].

From Kiel W. Leontief was invited to the National Bureau of Economic Research (NBER) in the U.S., where he developed the closed and the open input-output system, the theory and the characteristics of the input-output inverse [99]. By 1932, he was at Harvard, and he took inspiration from Quesnay’s tableau economique that collected who produced and who spent what (1759) [104].

In 1936 Leontief published his first table based on 1919 Census data. In that paper [105] he described the quantitative input – output relations. Fig. 3.4 shows one of the first IO tables developed by Leontief.

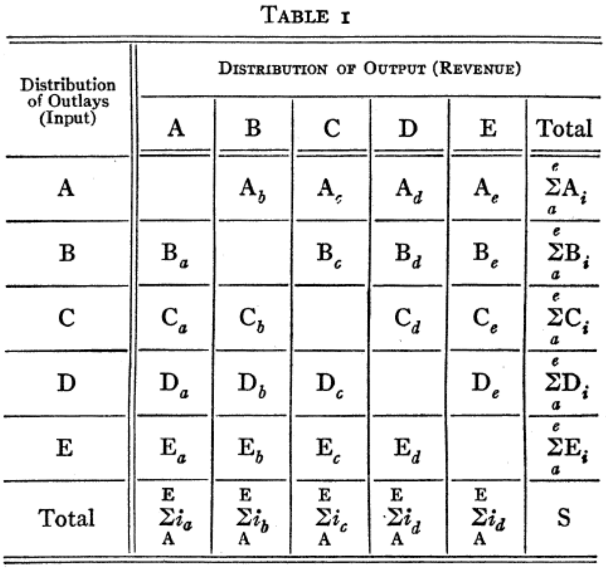

TABLE I

Distribution of Outlays (Input)	DISTRIBUTION OF OUTPUT (REVENUE)					
	A	B	C	D	E	Total
A		A_b	A_c	A_d	A_e	$\sum_{a}^{e} A_i$
B	B_a		B_c	B_d	B_e	$\sum_{a}^{e} B_i$
C	C_a	C_b		C_d	C_e	$\sum_{a}^{e} C_i$
D	D_a	D_b	D_c		D_e	$\sum_{a}^{e} D_i$
E	E_a	E_b	E_c	E_d		$\sum_{a}^{e} E_i$
Total	$\sum_{A}^{E} i_a$	$\sum_{A}^{E} i_b$	$\sum_{A}^{E} i_c$	$\sum_{A}^{E} i_d$	$\sum_{A}^{E} i_d$	S

Figure 3.4: One of the first tables implemented by Wassily Leontief [105].

IOA returned in Europe after the Second World War, subsequently to some programs, which were born due to the Marshall Plan, such as the System of National Accounts (SNA) and the ‘Association Scientifique Européenne de Programmation Economique à Long Terme’ [99]. As noticed by Leontief, after 1950s Europe passed USA in the IOA research field.

In Europe the history of the IOA cannot be separated from the history of the National Accounting. The necessity to merge national accounts and IOA became important after the publication ‘Input-Output and National Accounts’ [106] written by Richard Stone, who in 1984 received the Nobel Memorial Prize in Economic Sciences for developing a novel accounting model.

After obtaining this linkage between national accounts and IOA, the efforts was focused on the compilation of the Social Accounting Matrix and of the 'Make and Use' tables, able to interconnect commodities and industries in order to carry out a more specific input – output analysis.

In 1960s IOA was developed to take into account various environmental impacts through some exogenous variables added in the national accounts. Even Leontief [107], in one of his last papers, wrote about the necessity to use input – output tables to assess the environmental impacts such as pollution.

In the early seventies the oil crisis pushed the research to apply IOA to energy analysis, giving birth to the Net Energy Analysis [37].

In the eighties some attempts were made to summarize fifty years of developments in IOA which suggest the way to follow for the future [108].

Nowadays, IOA is widely used both in economics and in environmental sciences and has become one of the most important framework in Economics and Industrial Ecology as demonstrated by the great evolution over the years through the increasing number of publications concerning IOA as shown in tab. 3.1.

Table 3.1: Publications concerning IOA on Journal of Economic Literature [99].

Journal of Economic Literature: articles published referring directly on input - output analysis		
1960 - 1969	3	4,62%
1970 - 1979	19	29,23%
1980 -1989	18	27,69%
1990 - 1999	19	29,23%
(2000 - 2006)	6	9,23%
Total	65	100%

3.3.3 Mathematical model

Mathematically the IO model is a system of a set of n linear equation with n unknowns [94].

IOA can be applied to every kind of system: it can be an economy which consists of economic activities (sectors) or a system which consists of several components, interrelated among each other. In the following we refer to an economy composed by sectors.

In order to write a system of linear equations, the total production of every economic activity should be allocated between other economic activities and the final demand, that represents the final requirements of products of an economy. In other words, the production of every sector aims at providing the final demand; however other inputs are required by sectors to fulfill the final demand. Clearly, every economic activity produces different kind of products and, in order to enable its own production, a mix of different products is necessary: for this reason the n sectors are interrelated, having inter-sectorial flows. These flows can be measured in different units: monetary flows, physical flows etc. For instance the steel required by automobile sector can be measured in tons of steel or in euro of steel purchased from the 'steel sector'.

To sum up, the total production of one sector of the economy x_i, is shared between other sectors, that require a certain amount z_{ij} of the total production called intermediate demand, and the final demand f_i.

The balance, as already stated, forms a system of linear equations as shown in (3.6) :

$$\begin{cases} x_1 = z_{11} + z_{12} + \ldots + z_{1n} + f_1 \\ \vdots \\ x_i = z_{i1} + z_{i2} + \ldots + z_{in} + f_i \\ \vdots \\ x_n = z_{n1} + z_{n2} + \ldots + z_{nn} + f_n \end{cases} \tag{3.6}$$

In matrix notation:

$$\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \quad ; \quad \mathbf{Z} = \begin{pmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nn} \end{pmatrix} \quad ; \quad \mathbf{f} = \begin{bmatrix} f_1 \\ \vdots \\ f_n \end{bmatrix} \quad ; \tag{3.7}$$

Writing the system of linear equations (3.6):

$$\mathbf{x} = \mathbf{Zi} + \mathbf{f} \tag{3.8}$$

Where $\mathbf{i}$ is a column vector $(n \times 1)$ known as a "summation" vector consist in 1's everywhere, in order to allow the row sums of $\mathbf{Z}$.

Therefore the subsequent IO table can be displayed in tab. 3.2 where inputs are shown along the columns and outputs along the rows.

Table 3.2: Inter-sectorial flows IOT [94].

		Buying Sector				
		1		j		n
Selling Sector	1	z_{11}	…	z_{1j}	…	z_{1n}
		$\vdots$		$\vdots$		$\vdots$
	i	z_{i1}	…	z_{ij}	…	z_{in}
		$\vdots$		$\vdots$		$\vdots$
	n	z_{n1}	…	z_{nj}	…	z_{nn}

In order to implement the IO model some assumptions need to be set:

- The so called inter-sectorial flow from sector i to j, represented by z_{ij}, must depend on the total output of sector j x_j.

  This can be a reasonable assumption. For instance, consider the automobile sector that requires steel: the automobile sector will buy as much steel as required by its production. If the total production decreases, also the inter-sectorial flow z_{ij} will be decreased. Under this assumption there is the idea that the technology does not change in a specific time frame: to produce a certain amount of output is needed a defined constant quantity of input.

  Therefore can be introduced the concept of technological coefficient or technical coefficient defined as follow:

  $$a_{ij} = \frac{z_{ij}}{x_j} \tag{3.9}$$

  $$0 < a_{ij} < 1 \tag{3.10}$$

  The last condition (3.10) expresses the productive condition, without which the sectors of the economy cannot satisfy the final demand.

  In summary Leontief's system works with constant returns to scale [94] that implies both constant technical coefficients and linear production functions: if the output level of an industry changes, the input requirements will change in a proportional way. Clearly, the assumption of constant technical coefficients fits better with physical units that are not affected by economies of scale in contrast with an IO model composed by monetary units.
- Each sector produce one product;

- There are not resource's constrains;
- Supply is assumed infinite and perfectly elastic; and there is no underemployment of resources [109].

Once the assumption of constant technical coefficients is accepted and a set of technical coefficients is defined, the system of linear equations (3.6) can be rewritten replacing the values related to inter-sectorial flows:

$$\begin{cases} x_1 = a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n + f_1 \\ \vdots \\ x_i = a_{i1}x_1 + a_{i2}x_2 + \ldots + a_{in}x_n + f_i \\ \vdots \\ x_n = a_{n1}x_1 + a_{n2}x_2 + \ldots + a_{nn}x_n + f_n \end{cases} \tag{3.11}$$

In the same way of (3.7) a matrix notation will be used:

$$\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} \quad ; \quad \mathbf{A} = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \quad ; \quad \mathbf{f} = \begin{bmatrix} f_1 \\ \vdots \\ f_n \end{bmatrix} \quad ; \tag{3.12}$$

Where $\mathbf{A}$ is the matrix of the technical coefficients that replaces the $\mathbf{Z}$ matrix, no longer required. The system in matrix notation will become:

$$\mathbf{x} = \mathbf{Ax} + \mathbf{f} \tag{3.13}$$

Considering the total production of each sector as unknowns and dependent on the final demand, the system of linear equations can be resolved through the following steps:

$$(\mathbf{I} - \mathbf{A})\mathbf{x} = \mathbf{f} \tag{3.14}$$

Where **I** is the identity matrix, already defined here (3.5).
In order to resolve the system, using the standard matrix algebra, the resolution will be described as follow:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} \tag{3.15}$$

The term $(\mathbf{I} - \mathbf{A})^{-1}$ represents the Leontief's inverse or the total requirements matrix **L**:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} = \mathbf{L}\mathbf{f} \tag{3.16}$$

Because the factor refers to the amount of product that is invoked by a unit of final demand, **L** is also called the output multiplier [110].

Furthermore, the IO framework can be used to determine relative changes in total output based on an incremental change in final demand:

$$\Delta\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\Delta\mathbf{f} \tag{3.17}$$

Changes in final demands denoted with $\Delta\mathbf{f}$ in eq. (3.17), may be the result of a change both in the overall level of the final demand and in the expenditures, among the sectors, related to some specific goods or services (the final demand mix). Moreover, final demand data may be represented in several vectors, one for each final-demand classification, such as household consumption, exports, government expenditures, evaluating the impact of a change in the final demand for different entities [94]. Clearly, a change in the final demand causes a change in the total output vector $\Delta\mathbf{x}$. However, in order to estimate the impact of a new product in the economy, if the new product does not require a significant contribution in terms of final demand $\Delta\mathbf{f}$, it can be evaluated through eq. (3.17); alternatively, the entire technical structure of the economy may change.

3.3.4 The power series approximation

The Leontief inverse can be calculated also through a convergent series called power series. The series is already shown in (3.5).

In terms of IOA, the power series expansion:

$$(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{I} + \mathbf{A} + \mathbf{AA} + \mathbf{AAA} + \ldots = \mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \ldots \tag{3.18}$$

is a convergent series if **A** is a non-negative matrix and if the row sum of **A** is less than one [96, 111]:

$$\sum_{i=1}^{n} \left|\mathbf{A}_{ij}\right| < 1 \quad \text{for all j} \tag{3.19}$$

However this condition concerns economic IOT and it is not always complied in hybrid units IOA even if the series is convergent. A more accurate condition that has to be satisfied to verify the convergence of the series is:

$$\rho(\mathbf{A}) = \max_{1 \le i \le n} \left| \lambda_i(\mathbf{A}) \right| < 1 \tag{3.20}$$

(3.20) stated that the series converges when the spectral radius is less than one [96].

The power series approximation demonstrates the mathematical equivalence between IOA and process based methods: indeed, Leontief inverse is exactly the asymptote to which the power series converges, if some conditions are complied.

3.3.5 Exogenous Inputs and Endogenous Inputs

A system, which can be an economy consisting of sectors, or a micro-system composed by components, can be represented through the IO model. However defining IO model means also setting a system boundary which divides exogenous sectors or components from endogenous sectors or components. By referring to the case of an economy, exogenous sectors refer to those sectors that do not require any input for themselves, but provide inputs, in terms of resource flows, towards sectors within the system boundary (for instance an exogenous sector can be the environment). Endogenous sectors refer to those sectors that require inputs for their sustenance and provide outputs towards other sectors within the system boundary.

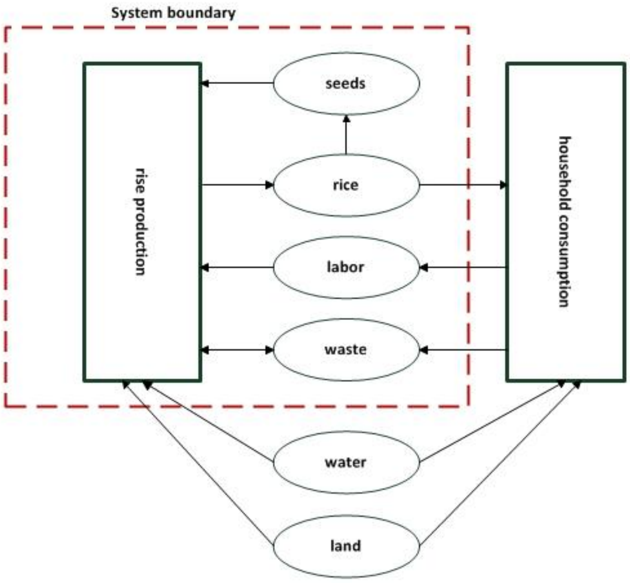

Figure 3.5: Endogenous and Exogenous inputs for a rural economy [110].

Fig. 3.5 shows a specific system boundary for a rural economy. Within the system boundary there are only sectors that require inputs from other sectors and ‘exogenous’ inputs [110]. These sectors are called ‘endogenous’. Outside the system boundary there are the final demand, represented by the household consumption, and two exogenous resources such as water and land that provide inputs to sectors within the economy and to the final demand, without requiring resources for their sustenance.

The main difference between endogenous and exogenous sectors is in the fact that endogenous sectors require inputs, whereas exogenous sectors do not require any input. Since exogenous sectors do not require any inputs for themselves, therefore their inputs to the economy can be considered direct inputs since no embodied resources have been used.

Mathematically the demand for exogenous inputs is dealt with a so called exogenous diagonal matrix [112] defined as the total external inputs from exogenous sectors associated with each output of endogenous sectors [113]:

$$b_i = \frac{R_i}{x_i} \quad \text{for all } i \tag{3.21}$$

Where:

- R_i is the resource input appropriated by each sector
- x_i the total output of the sector i
- b_i is the exogenous input coefficient

And in matrix notation:

$$\mathbf{b} = \begin{pmatrix} b_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & b_n \end{pmatrix} \tag{3.22}$$

In literature this diagonal matrix is usually used to link monetary IO tables with environmental burdens such as materials consumption, energy, exergy, land use, water, emissions etc. [113].

Once defined the diagonal matrix of the exogenous input coefficients, the demand for exogenous inputs can be calculated referring to (3.15) as follow:

$$\mathbf{x}^{ex} = \mathbf{b}\,(\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} \tag{3.23}$$

with $\mathbf{x}^{ex}$ defined as:

$$\mathbf{x}^{ex} = \mathbf{b}\,\mathbf{x} \tag{3.24}$$

$\mathbf{x}^{ex}$ represents the vector of the total demand for exogenous inputs.

3.3.6 Example: Embodied Energy in a two-sectors economy applying IO Analysis

Referring to the example in the paragraph 3.2.2, the aim is to apply IOA and evaluate and compare process analysis and IOA.

The assumptions are the same of the paragraph 3.2.2 and data are given in fig. 3.1.

Processing the data in an input – output table allows to illustrate the inputs and the outputs of the two economic sectors that compose the closed economy.

The matrix **A** in eq. (3.4) does not change. Indeed, in a mathematical point of view process analysis and IOA work in the same way. However in a real case the coefficients change because of the different levels of aggregation related to process based methods and IOA.

Referring to (3.3) and (3.4):

$$\mathbf{A} = \begin{pmatrix} 0,2\dfrac{\text{kWh}}{\text{kWh}} & 0,1\dfrac{\text{kWh}}{\text{euro}} \\ 0,05\dfrac{\text{euro}}{\text{kWh}} & 0,2\dfrac{\text{euro}}{\text{euro}} \end{pmatrix} \quad ; \quad \mathbf{f} = \begin{bmatrix} 2000\,\text{kWh} \\ 10000\,\text{euro} \end{bmatrix} \quad ; \tag{3.25}$$

Leontief matrix **L** can be calculated:

$$(\mathbf{I}-\mathbf{A})^{-1} = \mathbf{L} = \begin{pmatrix} 1,3\dfrac{\text{kWh}}{\text{kWh}} & 0,2\dfrac{\text{kWh}}{\text{euro}} \\ 0,1\dfrac{\text{euro}}{\text{kWh}} & 1,3\dfrac{\text{euro}}{\text{euro}} \end{pmatrix} \tag{3.26}$$

In (3.26) the Leontief coefficients are greater than technical coefficients because they represent direct and indirect requirements per unit of output instead of technical coefficients that stand for direct requirements per unit of output.

Direct plus indirect contributions, which are required to comply with the final demand, can be calculated as absolute terms applying eq. (3.16):

$$\mathbf{x} = \begin{bmatrix} 4095\,\text{kWh} \\ 12756\,\text{euro} \end{bmatrix} \tag{3.27}$$

The results can be evaluated considering the fig. 3.3. The result referred to the energy sector is the asymptote of the cumulative curve in fig. 3.3.

As mentioned previously, the process analysis suffers from truncation error, otherwise IOA carries out a complete analysis if data are specific and levels of aggregation are detailed.

3.3.7 Types of IOTs

Many types of input – output tables (IOTs) can be found in literature. The differences are both in mathematical model and in the structure of the table because there is not strictly methodology and IOA can be applied to different systems and economies, as already stated.

In this paragraph types of IOTs at macro-economic scale will be described and compared from an environmental point of view, classifying IOTs according to units of measurement used in tables.

In detail, types of IOTs considered are three:

1. Monetary Input – Output Table (MIOT) and its extension to include environmental burdens through the diagonal matrix (3.22) of the exogenous inputs.

2. Physical Input – Output Table (PIOT) based on physical flows of resources or materials

3. Hybrid units Input – Output Table based on the idea that every sector should have the unit of measurement that best represents the output of that sector.

Monetary Input – Output Table (MIOT)

The MIOT, as its name suggests, is a table that illustrates the monetary flows within the economy. It is the basic Leontief's table in a purely economic point of view.

The MIOT, also called Economic IOT (EIOT), presents and clarifies all the economic activities being performed for a specific country, pointing out how many goods and services produced by a certain industry in a given year are distributed among the industry itself, other industries, households, etc., and presenting the results in a matrix (row and column) format.

The economic input-output framework of the European System of Accounts (ESA 1995) consists of three types of tables [114, 115]:

- Supply tables
- Use tables
- Symmetric tables

Supply and use tables provide a detailed framework of the supply of goods and services by domestic production and imports and the use of goods and services for intermediate consumption and final use. Final use consists of consumption by households, government expenditures gross capital formation and exports [115].

Moreover supply and use tables give information about production processes, interdependency between industries, the use of goods and services and information about income generated.

The supply table shows the origin of flows while the use table shows their destination [116].

A supply table illustrates the supply of goods and services by product and by type of supplier, distinguishing supply by domestic industries and imports from those of other countries. A simplified supply table is shown in tab. 3.3.

The use table is a product by industry based table. A use table shows the use of goods and services by product and by type of use, as intermediate consumption by industry, final consumption, gross capital formation or exports. Moreover the use table shows the value added by component and by industry. A simplified use table is shown in tab. 3.4.

Table 3.3: Supply Table [115].

Supply Table					
	Agriculture	***Industry***	***Service activities***	***Imports***	***Total***
Agricultural products	Output by product and by industry			Imports by product	Total supply by product
Industrial products					
Services					
Total	Total output by industry			Total imports	Total supply

Table 3.4: Use Table [115].

Use Table					
	Agriculture	***Industry***	***Service activities***	***Final uses***	***Total***
Agricultural products	Intermediate consumption by product and by industry			Final uses by product and by category	Total use by product
Industrial products					
Services					
Value added	Value added by component and by industry				Value added
Total	Total output by industry			Total final uses by category	

Supply and Use tables serve to compile an analytical framework as the symmetric input – output table. The name symmetric refers to products by products tables and industry by industry tables. The application of products by products tables instead of industry by industry depends on the assumptions made and it also depends on the specific objective of the economic analysis.

The construction of the symmetric IOT requires supply and use tables and it is based on the following relations:

Total supply by product = Total use by product
Total input by product = Total output by product

A simplified symmetric input – output table is shown in tab. 3.5.

Symmetric IOT allows to describe processes and transactions of products within the national economy in great detail, synthetizing the information provided by supply and use tables.

The latter table is also used in calculating the cumulated coefficients, by the Leontief-inverse.

Table 3.5: Symmetric IOT [115].

Symmetric IOT					
	Agricultural products	***Industrial products***	***Services***	***Final uses***	***Total use***
Agricultural products	Intermediate consumption by product and by homogeneous units of production			Final uses by product and by category	Total use by product
Industrial products					
Services					
Value added	Value added by component and by homogeneous units of production				
Imports for similar products	Total imports by product				
Supply	Total supply by homogeneous units of production			Total final uses by category	

Extending Monetary IO Models with Physical Accounts

As mentioned above, MIOTs can be extended to take into account environmental burdens associated with economic activities.

This type of method was already used in the areas of energy in studies concerning Net Energy Analysis [37]. Furthermore, the integration of material accounts in physical units into economic input-output models was first explored by Leontief [112].

The procedure to merge material flow analysis and MIOT uses the concept of endogenous and exogenous inputs explained in paragraph 3.3.5. The system boundary comprises the economic activities that exchange monetary flows. Outside the system boundary, the environment provides the exogenous inputs in term of energy, exergy, materials, resources etc. to some selected sectors of the economy, which have a direct interface with the environment.

In mathematical terms, referring to the eq. (3.23), matrix **A** will be compiled by technical coefficients defined as the ratio between the monetary inter-sectorial flow and the total monetary output of the sector under consideration, in a purely economic based approach. Therefore, in order to extend the MIOT for environmental accounting, the exogenous input coefficient (3.21) will be defined as the ratio between the exogenous input in physical terms and the total monetary output of the sector that has a direct interface with the environment (for instance Mining and Quarrying sector, which extracts resources from the environment).

The possibility to extend the MIOT, in order to take into account environmental burdens, gave birth to new kind of IOA such as Economic Input – Output Life Cycle Assessment (EIOLCA). The EIO-LCA methodology complements the economic input-output analysis by linking economic data with resource use (such as energy, ore, and fertilizer consumption) and/or environmental impact categories (such as greenhouse gases emissions) [117].

Physical Input – Output Table (PIOT)

Material Flows Analysis (MFA) and IOA find a meeting point in Physical Input – Output Tables (PIOTs). PIOTs are able to describe material and resource flows within the sectors of the economy, in particular on inter-industry relations, separating material inputs used for production processes from those directly delivered to final demand [118].

PIOTs generally use a single unit of mass to describe physical flows among industrial sectors of a national economy [119]. In this way PIOTs were capable of fulfilling mass balances.

Table 3.6: Scheme of a Physical Input Output Table [119].

PIOT (in physical terms)	
1st quadrant	***2nd quadrant***
Interindustry deliveries	Final demand; Residuals
3rd quadrant	
Primary resource inputs; Imports	

Tab. 3.6 shows the typical structure of a PIOT. The first quadrant describes the flows exchanged among the sectors of the economy. The second quadrant shows the final demand of materials and PIOT also provides to take account of wastes

and residuals as shown in the table. The third quadrant refers to the input quadrant that contains all primary material inputs to the economic system, which usually are materials coming from domestic extraction or imports.

PIOTs exist for five countries: The Netherlands, Germany, Denmark, Italy and Finland. Furthermore, a preliminary PIOT for the European Union is based on information from the German and Danish PIOT, scaled up to EU levels. However the implemented PIOTs are outdated and with lack of information or with few sectors considered [120]:

- Netherlands PIOT for 1990 includes different kinds of materials and resources such as cement, concrete and concrete products, plastics, non-ferro metals, paper and paper products, iron, steel and zinc, energy.
- Germany PIOT for 1990 and 1995 includes in the account total mass, energy, water, and other materials in a table composed by 60 aggregated sectors.
- Denmark PIOT for 1990 includes the account of total mass, animal and vegetable products, stone, gravel and building materials, energy (ton and PJ), metals, machinery, apparatus and means of transport, chemical products and fertilizers, plastics and plastic products, wood, paper and commodities thereof, other commodities, packaging, nitrogen content in a table composed by 27 aggregated sectors.
- Italy PIOT for 1995 includes the account of total mass and carbon in a table composed by 5 aggregated sectors.
- Finland PIOT for 1995 takes into account total mass in a table composed by 30 aggregated sectors.
- EU PIOT for 1995 considers mass flows for 7 aggregated economic sectors.

Even if PIOT can seem the best accounting method for resources assessment, it suffers from a great number of limitations. Firstly the flows in PIOTs are counted in a single unit of measurement, usually tons. In this way small flows of materials but with a high impact on the environment cannot be taken into account. Furthermore, a major methodological weakness with regard to PIOTs compiled so far is that there are no standardized accounting methodologies [119]. Finally compiling PIOTs is time-intensive and the data are not always available for all the economic sectors under consideration and information about resources or materials are difficult to trace. The evidence of that is in the limited number of PIOTs available in literature.

MIOT vs. PIOT: what makes differences?

Recently several publications are aimed at comparing the technical coefficients matrix of PIOTs and extended MIOTs, in order to choose the best method to evaluate embodied resource flows within the economy.

Hubacek and Giljum [121] asserted that physical input–output models are more appropriate to account for direct and indirect resource requirements (such as land area, raw materials, energy, or water). In a reply to that paper, Suh [122] demonstrated that waste is misspecified in the PIOT used by Hubacek and Giljum, making inconsistency mass balance. Suh concluded that different results between PIOT and MIOT do not indicate the superiority of the physical model over the monetary model, but they are the consequence of a different treatment of wastes and residuals.

The most important difference between PIOT and MIOT, is the purpose by which the two tables are designed. PIOT has a purely environmental purpose, conversely MIOT does not only have environmental purpose but also it is compiled to have a detailed picture of all economic activities [123].

However PIOT and MIOT, should be ideally the same: indeed multiplying PIOT by the prices of products means obtaining MIOT. Some attempts are made to find a price vector that could make the conversion possible. Nevertheless, a PIOT is not simply a unit conversion of a MIOT and cannot be derived only by multiplying the MIOT with a vector of prices per tons of material input for each cell. It is possible to make this conversion through the use of a prices matrix that does not have a meaningful economic interpretation [123].

Table 3.7: MIOT and PIOT for Germany economy [123]. Primary, secondary and tertiary sectors are represented by numbers 1, 2, 3.

Three sector intermediate use and final demand in a MIOT and a PIOT, Germany, 1990

	MIOT, in million DM				**PIOT, in million tons**			
	1	2	3	Final demand	1	2	3	Final demand
1	40	89	80	12	2248	1442	336	84
2	33	654	427	1055	27	1045	206	708
3	28	363	2327	334	5	69	51	36

A-matrices in the three sector MIOT and PIOT

	MIOT, in million DM			**PIOT, in million tons**		
	1	2	3	1	2	3
1	0,18	0,04	0,01	0,35	0,51	0,29
2	0,15	0,3	0,08	0,00	0,37	0,18
3	0,12	0,17	0,42	0,00	0,02	0,04

In tab. 3.7, PIOTs and MIOTs for Germany economy (1990) are implemented in order to evaluate the quantitative differences.

As shown in the tab. 3.7 the coefficients matrix changes substantially comparing MIOT and PIOT. For instance, the PIOT technical coefficients along the row relating to tertiary sector are extremely lower than MIOT. Indeed in PIOTs, services have a low environmental impact due to how the table was designed.

The core of different results that arise from physical and extended monetary input – output models, is the different nature of PIOTs and MIOTs, which are not comparable because of the absence of a homogenous vector of prices able to convert a PIOT in a MIOT [124].

Hybrid units Input – Output Table

In recent years, some specialists have called for the development of so called "hybrid" models that actually describe simultaneously physical flows and monetary flows in an economy [125].

Working under hybrid units IOT (or mixed units IOT) requires to build a dual accounting both in physical and monetary terms in order to merge these two approaches from a macro-economic point of view. However in the past, this type of IOT was limited by difficulties related to availability of several monetary and physical data. Nowadays current data on both physical and economic dimension are mostly available and the account can be enabled.

In literature, Konijn et al. [126] and Hoekstra [127] have used both physical and monetary units in an input – output table, introducing the mixed-unit input-output model.

Recently an interesting study about mixed units model for a hybrid energy input – output model was proposed by Mayer (published by the German Federal Statistical Office) [128] based on Bullard and Herendeen works. Tab. 3.8 shows the hybrid energy IOT presented for the 16-th International Input-Output Conference.

Table 3.8: Hybrid Energy IOT [128].

Hybrid Energy IOT						
	Homogenous branches		***Final uses***	***Total use***	***Imports***	***Output***
Products	***Energy sectors***	***Others branches***				
Energy branches	Energy consumption (Terajoule)					
Others branches	Intermediate consumption (EUR)		Final demand (EUR)	Total use (EUR)		
	Gross value added (EUR)					
Output	Terajoule	EUR				

In a hybrid units input – output table the outputs of the sectors have the same unit of measurement. For instance in tab. 3.8 energy branches have TJ as unit of measurement instead of ‘other branches’ of the economy compiled in euro. This table refers to inter-sectorial flows and final demand, therefore the technical coefficients defined in (3.9) will be in mixed units:

$$\mathbf{A} = \begin{pmatrix} \frac{\mathrm{TJ}}{\mathrm{TJ}} & \cdots & \frac{\mathrm{TJ}}{\mathrm{EUR}} \\ \vdots & \ddots & \vdots \\ \frac{\mathrm{EUR}}{\mathrm{TJ}} & \cdots & \frac{\mathrm{EUR}}{\mathrm{EUR}} \end{pmatrix} \tag{3.28}$$

where:

- $\frac{\mathrm{TJ}}{\mathrm{TJ}}$ is the unit of measurement of technical coefficients related to flows from energy sector to energy sectors
- $\frac{\mathrm{TJ}}{\mathrm{EUR}}$ is the unit of measurement of technical coefficients related to flows from energy sector to other branches
- $\frac{\mathrm{EUR}}{\mathrm{TJ}}$ is the unit of measurement of technical coefficients related to flows from other branches to energy sectors
- $\frac{\mathrm{EUR}}{\mathrm{EUR}}$ is the unit of measurement of technical coefficients related to flows from other branches to other branches

As mentioned above, the technical coefficients matrix has to comply to condition (3.20).

Hybrid-unit input – output models can play an important role in modeling materials and energy flows free from the price inhomogeneity and the pitfalls of single-mass unit Physical Input-Output Tables [129].

Future developments in hybrid units IOA depend on the intention to consider different kinds of outputs capable of mixing social, environmental and economic dimensions. From a sustainable point of view, efforts in research have been made to understand “relationship between consumption activities and well-being”. A hybrid – unit input – output table was implemented trying to take into account monetary transactions, physical flows of resources and time use as an indicator of the social dimension [130]. The author called the IOT a “Magic Triangle Input-Output Table” in referring to the possibility to merge the three dimensions of the sustainability.

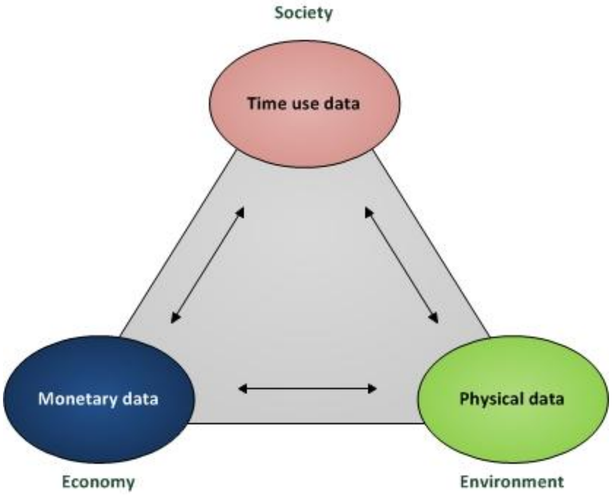

Figure 3.6 Interconnections between society, economy and environment in 'Magic Triangle IOT' [130].

The production function in that model will develop as follows, in order to consider time inputs, physical inputs and monetary inputs as factor of production:

$$x_j = F\left(z_{1j}, z_{2j}, \ldots, z_{nj}, t_j, r_j\right) \tag{3.29}$$

where:

- z_{ij} = intermediate inputs from i used in production of j
- t_j = time input to production in j
- r_j = material inputs to production in j

The latter model is only one example of the power of hybrid units IOT, capable of integrating some different aspects of the human activities in order to minimize resource consumption without sacrificing human well-being.

Moreover, these methods allow to follow the new developments in LCA described in paragraph 2.3.4.

3.3.8 Current IO methodologies

Current IO methodologies in environmental IOA refer to all the methods that do not necessarily use the best technique but are based on the compromise between availability of data and the best technique able to process those data.

Nowadays, as mentioned above, data on monetary flows in the layout of an IOT are widely available. Usually these data are collected by National Statistical

Institutions. Data on environmental flows of materials, resources and emissions are also widely available but not in the form of an IOT.

The models mostly used nowadays, capable of merging these data, in order to carry out an IOA, will be described in this paragraph.

These models are based on the Herman Daly matrix [131] shown in fig. 3.7.

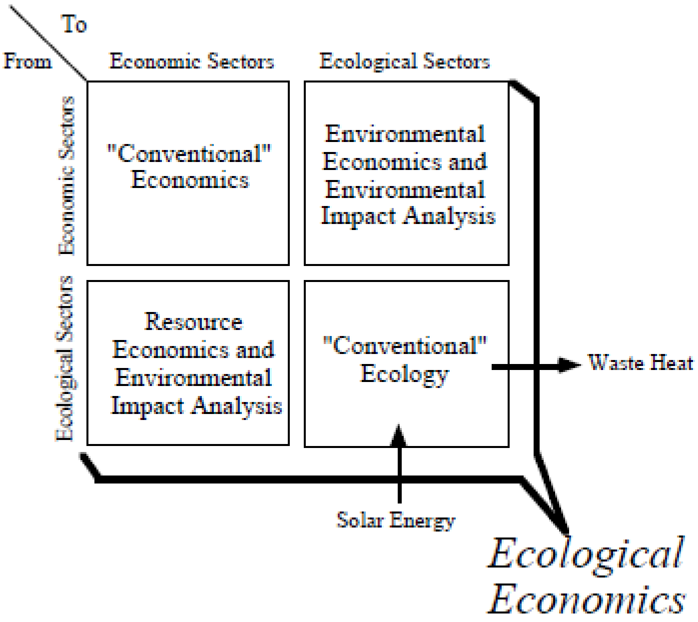

Figure 3.7: Linkage between Economy and Ecology in H. Daly matrix [131].

The matrix in fig. 3.7 reminds the form of an IOT where outputs are illustrated on the rows and inputs are shown in columns. The first quadrant can represent the flows of resources or money within the economic activities; the study of these flows provides a conventional economic analysis. The fourth quadrant can represent flow of resources within the environment, providing a conventional ecological analysis. The most interesting quadrants are the second and the third one. The second quadrant shows the output of the economic activities in terms of environmental impacts (for instance wastes produced by economy). The third quadrant refers to the primary inputs from the environment to the economy. Daly claims for an inseparable analysis between economics and ecology, calling the new academic field ‘Ecological Economics’.

Ecological Economics aims at tracing flows of resources exchanged between techno-sphere and biosphere [132].

From this point of view, new methods based on IOA catch Daly’s idea and propose a mathematical interpretation of this concept.

Methods such as Economic Input – Output Life Cycle Assessment (EIOLCA) and Environmentally Extended Input – Output Analysis (EEIO) evaluate the relationship between economic activities and downstream environmental impacts [133].

Environmentally Extended Input – Output Analysis (EEIO)

As stated in paragraph 3.3.7, monetary input-output tables (MIOT) shows value of economic transactions between different sectors in an economy, including output for exports, capital formation and final government and private consumption. Such monetary IO tables can be ‘extended’ with environment-related information for each sector, such as its emissions, primary (natural) resource use, land use and other external effects per sector [134].

Environmentally extended input-output (EEIO) is based on this extension of the MIOT to include some environmental effects into the account. Indeed, the mathematical model is the one describes in eq. (3.23) where **A** shows the domestic intermediate industry output (in monetary terms) that is required to produce one unit of output of the sector that corresponds to the column; **f** denotes the final demand by households and governments as final consumers, and by exports in monetary terms; and **b** shows the amount of pollutants emitted and natural resources consumed to produce one unit monetary output of each industry in a diagonal matrix defined as (3.22).

EEIO is generally used to accomplish one or both of two major goals [133]:

- To calculate the hidden, upstream, indirect or embodied environmental impacts associated with a downstream consumption activity.
- To calculate the amount of embodied environmental impact in goods traded between nations.

The potential application areas for EEIO models are the following [134]:

- Environmental problem analysis, that is analysis of life cycle environmental impacts of products.
- Prospective effect analysis of policies: this involves the ex-ante prediction of effects of policy measures and may include trend and scenario analysis with some implications such as environmental taxations.
- Monitoring and ex-post effect analysis of policies: this involves the ex-post analysis of impacts and effectiveness of policy measures.

Recently EEIO have been used for analysis of the global carbon, water, ecological, nitrogen and biodiversity/wildlife footprints, emission of pollutants, the degradation or harvest of natural resources and the loss of biodiversity [133, 135].

Even if EEIO seems to be a powerful framework in supporting information-based environmental and economic policies, it suffers from several well-known limitations [133]:

- Level of aggregation: this limitation is shared with every type of input – output table and concerns the assumption that every sector produces only one single product. Increasing the number of sectors means decreasing the error related to this issue.
- Input-output tables may not capture all activities in the economy. For example, they may exclude unpaid work and will not generally include direct impacts by consumers that do not involve purchases from economic sectors.
- As mentioned previously, input – output model has constant returns to scale.
- Data are not collected with a standard methodology in every country, decreasing the accuracy of data at global scale.
- Inventories of environmental impacts, especially at wide – economy level, often reflect a mix of empirically measured data and modeled estimates, introducing errors and uncertainties in the analysis.

Despite these limitations, EEIO continues to grow up in popularity, increasing the number of publications concerning the application of this method to assess environmental impacts related to human activities.

Economic Input – Output Life Cycle Assessment (EIOLCA)

To address the problem of subjective boundary in LCA (see paragraph 2.3.3), Lave and colleagues proposed to apply economic input – output tables for a LCA purpose [136]. As mentioned in the paragraph concerning the LCA, a system boundary must be defined in order to perform a LCA analysis: in EIOLCA model the system boundary is the entire economy of a country.

Lave and colleagues implemented the IOA using the 498 × 498 commodity sector direct requirements matrix published by the U.S. Department of Commerce as a part of 1987 U.S. input – output tables [113].

Several environmental impacts are covered with this analysis: global warming, acidification, energy use, non-renewable ores consumption, eutrophication, and conventional pollutant emissions.

The mathematical model is the same already explained here (3.23) and for EEIO. Indeed, EIOLCA uses monetary tables to compile the coefficients matrix $\mathbf{A}$ and compile the vector of the final demand $\mathbf{f}$. Environmental burdens are collected in the diagonal matrix in eq. (3.22).

An interesting concept introduced by S. Joshi in EIOLCA method is the way to handle the environmental impact of a new specific product, or the way to disaggregate existing industrial sectors to evaluate environmental impact of a specific product, already included in the economy [113].

EIOLCA is different from other methods because it allows to include the use phase of products and the end-of-life of products. However the strong assumption made is that technical coefficients remain constant during the entire life cycle of the product under consideration [113].

Nevertheless, EIOLCA model suffers from some limitations [136]:

- Even with actual 519 economic sectors represented, the amount of disaggregation may be still insufficient for a complete LCA analysis.
- To include use phase and disposal phase new rows and columns in the requirements table should be compiled or, alternatively, particular sectors could be disaggregated to reflect specific processes or products.
- Uncertainties can arise from basic source data, data referred to old IOTs and from the assumptions made in IO model already explained in paragraph 3.2.3.
- Imports are treated with the same productive structure of the country considered. Obviously, this is not a reasonable assumption considering that processes depend on the country where they take place.

The advantages related to EIOLCA concern the possibility to have a wide – economy boundary, a comprehensive framework that allows fast and inexpensive analysis and the opportunity to compare different LCA strategies for analyzing particular supply chains, improving the confidence in results, or helping to identify errors [97].

3.3.9 IOA: benefits and limitations compared to Process Analysis

IOA presents benefits and limitations such as process-based analysis. Referring to advantages related to process analysis, described in the paragraph 3.2.4, the benefits of an IOA are the following [97]:

- results are economy-wide, considering a large number of economic sectors
- allows for systems-level comparisons
- uses publicly available, reproducible results
- provides for future product development assessments
- provides information on every commodity in the economy

Nevertheless IOA presents the following disadvantages compared to a process-based analysis [97]:

- product assessments contain aggregate data

- difficult evaluation of processes
- must link monetary values with physical units for an environmental IOA
- imports treated as products created within economic boundaries
- availability of data for complete environmental effects
- difficult to apply to an open economy (with substantial non-comparable imports)
- uncertainty in data as in process analysis

3.4 Hybrid Analysis

Hybrid analysis is the name of the method aimed at combining process analysis and input – output analysis. In theory process analysis and IOA provide the same results if system boundaries and data are the same as shown in paragraph 3.3.6. However, IOA is not available at the necessary level of detail because of the aggregation of the sectors. Process analysis zooms in on the process under consideration, describing in detail the chain of inputs close to the first stage, cutting off last stages and introducing a truncation error.

Therefore, IOA and process analysis seem to have opposite advantages that could be gained mixing the methods in a hybrid analysis. For instance, truncation error introduced by process analysis can be minimized using IOA and, moreover, errors introduced by aggregation in IOA can be minimized using process analysis [37].

In order to perform a hybrid analysis, Bullard et al. stated that embodied resources to the first or to the second stage have to be calculated by the use of process analysis, while some of the input materials, typical of an IO sector, can be determined by using IOA [37].

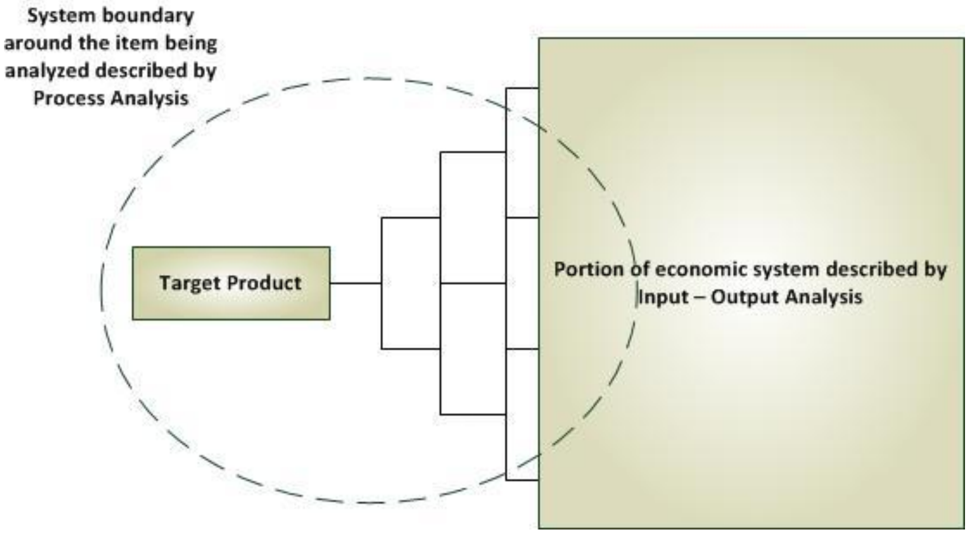

Figure 3.8: System boundaries in hybrid analysis [37].

Fig. 3.8 shows an example of hybrid analysis described by Bullard et al. [37]: system boundary related to process analysis is close to the target product, otherwise system boundary related to IOA describes the last stages represented by the sectors of the economy.

Recently, Treloar [51] categorizes this method into types:

- Process-based hybrid analysis
- Input/Output-based hybrid analysis

Process-based or 'tiered' hybrid analysis involves the derivation of the direct and downstream requirements and some important lower order upstream requirements of the product system under study using detailed process analysis while remaining higher order requirements are covered with IOA [49, 51], as described by Bullard et al.[37].

This method assimilates input/output-based analysis to complex parts of upstream processes of material production and thus obviates the incompleteness inherent in process analysis [137].

IO - based hybrid approach is carried out by disaggregating industry sectors in the IO table, adding process analysis data into the input-output model [138]. In this way, detailed process-specific data can be fully utilized without double counting [49]. Treloar, in his studies [51], has suggested the following procedure: as the first stage, the LCA assessment is performed mainly with IOA data. Subsequently, the entire production system is decomposed into groups of processes called paths, which are classified according to the relative contribution to the final LCA results. Ultimately, the process data can be collected till the desired level of accuracy is reached [139].

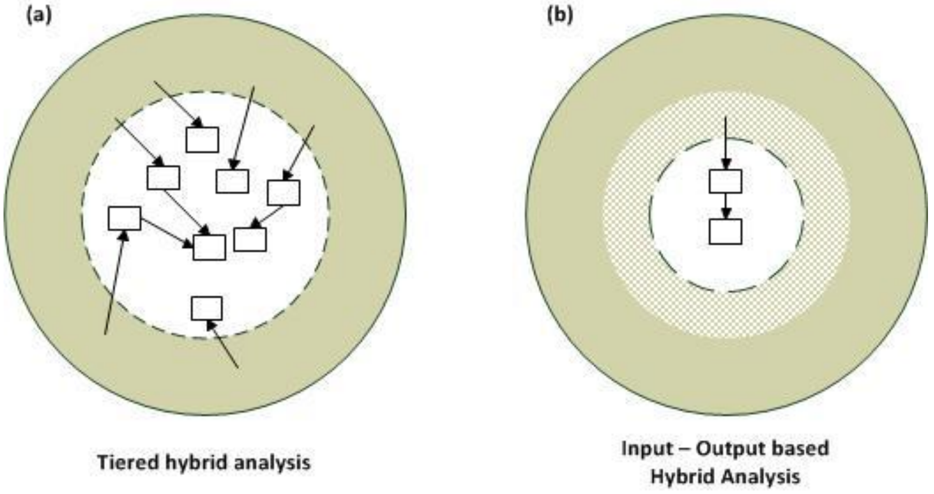

Figure 3.9: **Differences between tiered hybrid analysis (a) and IO based hybrid analysis (b) [138].**

Fig. 3.9 shows how tiered hybrid analysis works, using process analysis for first stages and IOA for the last ones, and how input-output based hybrid analysis is developed, using process data into IO model.

Both tiered hybrid analysis and input – output based analysis are tools created in order to reduce errors in LCA analysis. Hybrid methods are step-forward for the improvement of LCA and they lend themselves to be the basis for future developments.

4. Exergy Cost of Working Hours

4.1 Introduction

In economics, labor is a measure of the work done by human beings. Industry sectors consume human resources in the form of labor and workers consume natural resources in order to sustain their work activities [77].

In paragraph 2.5 the attempts made to assign a cost in terms of resource consumption to human labor were described.

However, the issue about assigning an ecological cost to human labor remains unresolved. More and more recent papers claim for the necessity to include resource consumption of human labor into account, trying not to fall in the trap of double accounting [77].

The issue of assigning a content in terms of resource consumption to human labor has several causes:

- Economics and Ecology diverge in the treatment of human labor [7]. Indeed, in economics, human labor is a factor of production and, for this reason, it is considered as an input in the production chain. Nevertheless workers are also consumers of goods and services, and from an ecological perspective they spend resources to make available their labor (see paragraph 1.2.3).
- Human labor can be seen as a recycling of resources within the economy as demonstrated by Szargut (see paragraph 2.5.3).
- If human labor is proven to be the origin of a part of resource consumption, how to quantify this portion? What is the temporal domain related to embodied resources in human labor and what is the unit of measurement capable of representing the output of human labor (hours, money etc.)?

This chapter aims to answer these problems by trying to find a solution for the issues previously described., through the use of the IO methodology.

Summary of the models introduced in this chapter

Initially, the standard IO model will be explained. The standard IO model is based on models that were described in paragraph 3.3.8, such as EIOLCA and EEIO. These models employ monetary IO tables and associate them with the diagonal matrix of the exogenous inputs. Usually the diagonal matrix of the exogenous inputs covers several environmental impacts such as global warming, energy use, pollutant emissions etc. In this work, the matrix under consideration will be filled in with the non-renewable primary exergy required by a country.

The standard IO model is shown in fig. 4.1 (a), which describes the following steps: the environment provides resources to the economic sectors (the only entities that are endogenous), and economy employs these resources to produce goods and services in order to fulfill the total final demand.

Subsequently, how to divide the total final demand of goods and services in the final demand of workers and the total final demand except workers requirements, will be explained.

Once the final demand is shared between workers, households, export etc., the system boundary, which divides exogenous flows from endogenous flows, can be extended in order to include the 'labor sector' as a new sector of the economy. The latter receives goods and services from economic sectors and provides working hours as the output. Fig. 4.1 (b) illustrates the novel IO model, which includes labor sector as endogenous.

In this chapter, the standard IO model will be explained, a method for dividing final demand will be introduced and a novel IO model capable of including labor sector as endogenous will be presented.

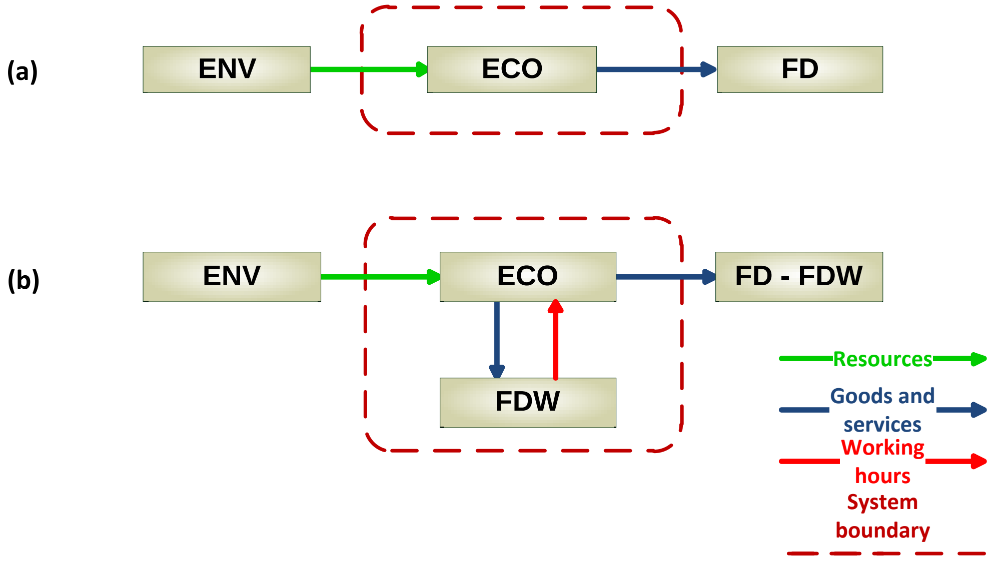

Figure 4.1: (a) standard IO model; (b) IO model including working hours as endogenous. ENV: environment; ECO: economy; FD: final demand; FDW: final demand of workers.

4.2 Computing Exergy Costs applying IOA

In this analysis will be evaluated embodied exergy or exergy cost in goods and services by means of IOA.

Once the exergy numeraire was selected as measure of resource consumption (see chapter 1), it is possible to calculate exergy requirements of every type of entities within the economy through the use of the input – output model. As stated in chapter 3, IOA in monetary terms can be extended to take into account environmental burdens - in this case the exergy requirements - related to human activities, applying the model described in paragraph 3.3.5.

4.2.1 Direct exergy requirements in IOA

In chapter 1 the benefits of using exergy numeraire as a measure of the depletion of the resources were described. Exergy allows to distinguish energy quality and can take into account various forms of energy.

In IOA, the system boundary refers to an economy of a country, composed by economic sectors, and since the MIOTs are available annually, the year will be considered as the time domain of the analysis.

The primary exergy required by the economy in one year is the Total Primary Exergy Supply (TPExS), the analogous of the Total Primary Energy Supply (TPES) but in terms of exergy. Since exergy is capable of including a huge number of energy forms, such as minerals, biological materials etc. [140], the account of the primary exergy required by a country could become difficult to assess. Nevertheless, the aim of this study is to evaluate exergy requirements from a sustainable point of view. For this reason, only the consumption of the non-renewable exergy is considered in order to follow the concept of the ecological cost proposed by Szargut [91].

Since energy resources are usually measured in energy units, the exergy of an energy resource can for simplicity often be expressed as the product of its energy content and a quality factor (the exergy-to-energy ratio) for the energy resource [34]. Tab. 4.1 collects these quality factors.

Table 4.1: Quality factors for some common energy forms [34].

Energy forms and quality factors	
Energy Forms	***Quality factors***
Mechanical Energy	1,00
Electrical Energy	1,00
Chemical fuel Energy	1,00
Nuclear Energy	0,95
Sunlight	0,90
Hot steam (600 °C)	0,60
District heating (90 °C)	0,20 – 0,30
Moderate heating at room temperature	0,00 – 0,20
Thermal radiation from the earth	0,00

TPExS of non – renewable fuels for EU 27 from 2000 to 2006 is represented in fig. 4.2. The latter shows the increase in demand for non-renewable resources over the years.

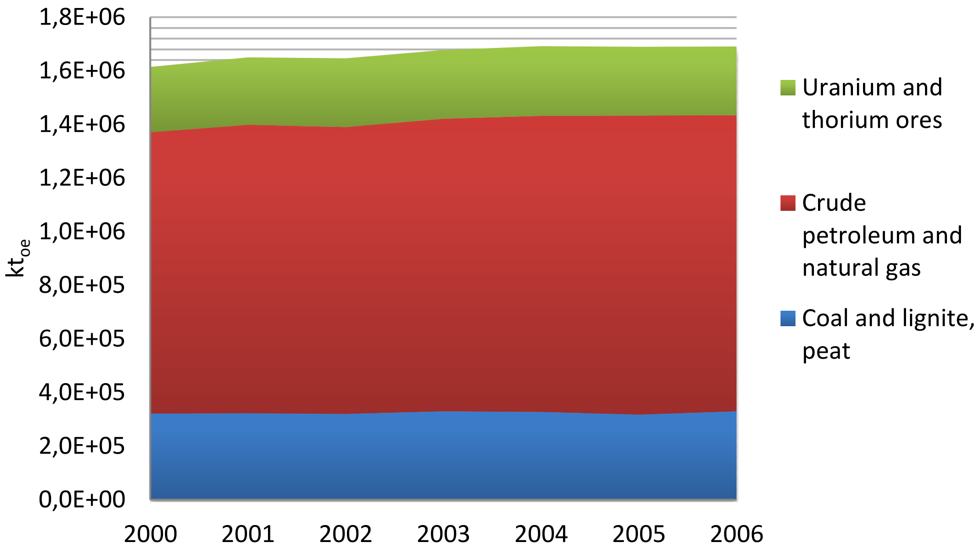

Figure 4.2: Total Primary Exergy Supply for EU 27 from 2000 to 2006 (Eurostat data).

Once defined the concept of non-renewable exergy as a measure of depletion of natural resources, direct exergy requirements can be associated with economic sectors of a country. The sectors of the economy that usually extract resources from the environment refer to the primary sector. For instance, Agriculture sector extracts biomass from environment, while Mining and Quarrying sector extracts mineral resources [112]. Then, these sectors exchange these resources with other sectors of the economy that transform them in goods and services to fulfill the final demand.

In this analysis non-renewable exergy natural resources are associated with appropriate economic sectors, which have a direct interface with the environment, through the use of the diagonal matrix that contains the direct exogenous inputs defined in eq. (3.22).

4.2.2 Categories of final demand

Human activities and economy have the objective to fulfill the final demand of goods and services. Final demand is the amount of specific goods and services that a consumer or a group of consumers want to purchase at given price.

In economics, the final demand of a country is shared between the following entities [115]:

- Final consumption expenditure by households
- Final consumption expenditure by non-profit organizations
- Final consumption expenditure by government
- Gross fixed capital formation (consists of resident producers' acquisitions, less disposals, of fixed assets during a given period)
- Changes in valuables
- Changes in inventories
- Exports

The IOA considers that the entire consumption of resources, in this case the Total Primary Exergy Supply (TPExS) of non-renewable natural resources, is allocated to these categories, since the objective of the economy is to provide goods and services in order to fulfill the final demand. In other words, all these categories function as perfect exergy dissipaters.

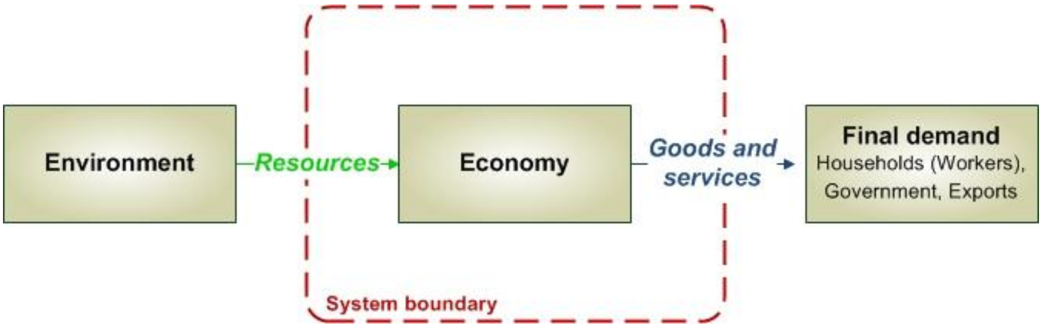

Figure 4.3: The scheme represents the flows exchanged between environment, economy and final demand. The system boundary divides endogenous flows from exogenous.

Fig. 4.3 shows the basic concept of environmental extended IO model: environment provides resources to economy, the latter transforms resources into goods and services and final demand consumes them. The system boundary is necessary in order to divide endogenous flows from exogenous ones.
The environmental IO model follows the structure of EEIO and EIOLCA discussed in paragraph 3.3.8. Therefore, referring to eq. (3.23), it is possible to write:

$$\mathbf{x}^{ex} = \mathbf{b}\,(\mathbf{I}-\mathbf{A})^{-1}(\mathbf{f}_{\text{households}} + \mathbf{f}_{\text{non-profit}} + \mathbf{f}_{\text{gov.}} + \mathbf{f}_{\text{cap. form.}} + \mathbf{f}_{\text{changes}} + \mathbf{f}_{\text{exp.}}) \quad (4.1)$$

where:

- **b** is the diagonal matrix defined in (3.22) and includes the exogenous inputs in terms of direct exergy requirements of sectors that have a direct interface with the environment such as Mining and Quarrying and Agriculture, since they need to extract resources from the environment [112].
- **I** is the identity matrix.
- **A** is the technical coefficients matrix defined in (3.12), set by means of the monetary input – output table. It represents the technology that sectors use to enable the production of goods and services.
- **f** is the final demand divided in the categories explained previously.
- $\mathbf{x}^{ex}$ is the vector of total exogenous demand defined in (3.24), which represents the vector of total exergy requirements in this analysis (the TPExS for a country).

The eq. (4.1) returns the vector of the total demand for exogenous inputs that is the total exergy cost required by the economy of the country under consideration.

Referring to eq. (3.16) the eq. (4.1) becomes:

$$\mathbf{x}^{ex} = \mathbf{b}\,\mathbf{L}\mathbf{f}_{total} \tag{4.2}$$

Eq. (4.2) expresses the eq. (4.1) by means of Leontief inverse **L**. The matrix product **bL** gives the matrix of the specific exergy cost per output of final demand of each sector (see paragraph 4.2.4); $\mathbf{f}_{total}$ is the total final demand, which contains all the categories that were listed previously.

The model described in eq. (4.2) takes into account all the categories of the final demand, since the economy of a country aims at producing all these outputs. In any case, IOA allows to perform an analysis concerning the relative changes in the final demand as described in paragraph 3.3.3: in this way the environmental impact, in terms of exergy cost of every category of the final demand, can be evaluated.

4.2.3 Exergy Cost of households

Several studies concerning households consumption have been carried out through the use of the IOA at macro – economic scale such as a country. For instance, these studies [141-144] compute the primary energy requirements (in some cases also greenhouse emissions) of households for, respectively, Brazil, Republic of Korea, Australia and Netherlands, using IOA in various forms (extended IOA or hybrid IOA).

Basic energy input–output analysis, as already explained by Bullard et al. [39], generates total requirements and requirements per consumption category, and is therefore suitable for describing and explaining the effect of household consumption [145].

Households, through the consumption of a complex and changing mix of goods and services, determine the major part of the resource consumption, therefore most of the environmental load in an economy can be allocated to households [144].

For instance, households consumption of goods and services can be constituted by the following function consumption items or classes of goods and services [115]:

- Food, beverages, and tobacco
- Clothing and footwear
- Housing, water, electricity, gas, and other fuels
- Furnishings, households equipment, and routine maintenance of the house
- Health
- Transport
- Leisure, entertainment, and culture
- Education
- Hotels, cafes, pubs, and restaurants
- Miscellaneous goods and services

The items under consideration depend on the number of sectors that compose the IOT: for instance if the IOT contains 40 sectors, 40 different goods and services will be counted in households final demand represented by the vector $\mathbf{f}_{\text{households}}$.

IOA enables the assessment of the environmental burdens of every kind of good or service required by households. Indeed, referring to eq. (4.1) and eq. (3.17) the exergy requirements of households can be easily evaluated:

$$\mathbf{x}^{\text{ex}}_{\text{households}} = \mathbf{b}\,(\mathbf{I}-\mathbf{A})^{-1}\mathbf{f}_{\text{households}} \tag{4.3}$$

where:

- $\mathbf{f}_{\text{households}}$ represents the households final demand,
- $\mathbf{x}^{\text{ex}}_{\text{households}}$ represents the demand for exogenous inputs related to the households consumption. Obviously, $\mathbf{x}^{\text{ex}}_{\text{households}}$ is just a part of Total Primary Exergy Supply (TPExS) of non-renewable natural resources contained in vector $\mathbf{x}^{\text{ex}}$, because households are not the only users of primary exergy embodied in goods and services (also exports, government expenditures etc. compose the total final demand).

The vector $\mathbf{x}_{\text{households}}^{\text{ex}}$ includes the non-renewable exergy cost of households final demand. In addition, the model allows to calculate the exergy cost of goods and services divided by classes. For instance, the model allows to calculate the non-renewable exergy cost related to the consumption of the goods ‘foods, beverages, and tobacco’ or other specific categories through the matrix of the specific exergy costs. The sum of the non-renewable exergy costs of all the classes will represent the total exergy requirements (direct plus indirect) of households.

4.2.4 Specific and Total Exergy Cost of goods and services

The implemented input – output model allows to achieve two types of results:

- Specific exergy cost
- Total exergy cost

Specific exergy cost is given by the matrix product **bL**, since the latter returns the direct and indirect exergy requirements per unit of output of a product or sector. In Bullard’s and Costanza’s works about Net Energy Analysis and in Treloar’s works these coefficients are called ‘embodied energy intensities’ [39, 41, 51].

Specific exergy costs are related to the final demand of a particular sector’s product. For instance the goods ‘foods, beverages, and tobacco’ will have its own specific exergy cost that will be multiplied only by the final demand of ‘foods, beverages, and tobacco’, obtaining the total exergy cost related to the production of that good.

Total exergy costs can be calculated as follow [146] :

$$\mathbf{c}_{\text{tot}}^{\text{ex}} = \mathbf{bL}\hat{\mathbf{f}} \tag{4.4}$$

where:

- $\mathbf{c}_{\text{tot}}^{\text{ex}}$ is a matrix containing the total exergy cost of every category of goods and services,
- **bL** is the product matrix that represents the specific exergy cost,
- $\hat{\mathbf{f}}$ is the final demand diagonal matrix, which was gained diagonalising the vector of the final demand.

The total exergy cost allows to evaluate the environmental impact of some classes of goods and services, pointing out the products that are the cause of major consumption of primary exergy.

4.3 Including Human Labor in IOA

In this paragraph, a novel method capable of including ‘labor sector’ as endogenous in IOTs, will be discussed. Firstly, a fully closed model will be described in order to introduce the concept of making endogenous the final demand. Then, issues related to understanding goods and services required by workers will be discussed and a method to separate households final demand from workers final demand will be proposed. Finally, the mathematical model and some examples will be illustrated and discussed.

4.3.1 A fully closed model

Several attempts have been made to include households consumption as endogenous factor in IOA.

For instance, Costanza tried to endogenize households and government expenditure in the input – output model [41] for energy analysis purposes, as already shown in tab. 2.1; in economics, Appelbaum tried to integrate household structure and industrial structure through an extension in the input – output model [147] and efforts along these lines were found in Duchin’s works [148].

The classic example of this approach is the analysis of the so-called Social Accounting Matrix (SAM), a square matrix that represents all the entities within the economy (Firms, Households, Government and 'Rest of Economy' sector) as buyers and sellers at the same time. Tab. 4.2 illustrates an example of SAM.

Table 4.2: Social Accounting Matrix [94].

	Prod.	*Cons.*	*Cap.*	*ROW*	*Govt.*
Production		C	I	X	G
Consumption	Q		D	H	
Capital Accum.		S			
Rest of World	M	O	L		
Govt.		T	B		

SAM was developed from the basic concepts of the circular flow of income and expenditures in an economy as shown in fig. 4.4 [94]. For instance, referring to the households, this matrix associates the row of labor coefficients in money values with the column of outlays of this income for consumption goods and services. It is said to be closed for households, since it makes household incomes and outlays endogenous [148].

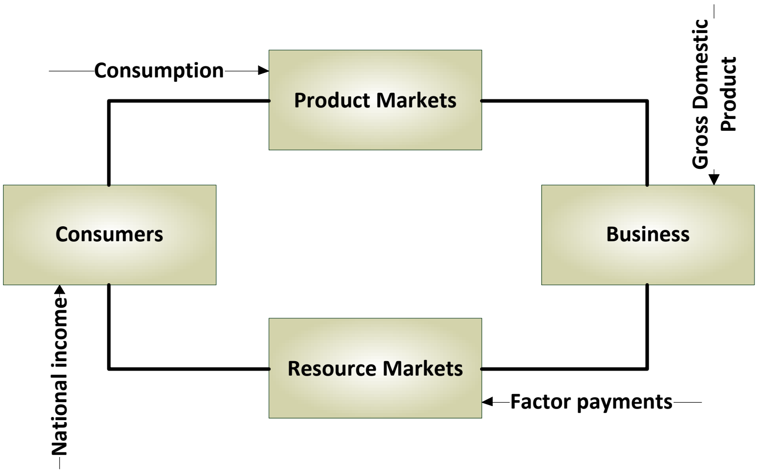

Figure 4.4: Circular flows of Income, Expenditure and Market in a SAM [94].

The matrix SAM, like a fully closed Leontief model, is a square matrix for which the row and column sums are identical. In a manner similar to the basic input–output framework, it is possible to define part of the economy to be exogenous, in order to “open” the input–output model.

However, considering an economy where the consumption or the final demand is totally endogenized, the input – output model will reduce to:

$$\begin{aligned} \mathbf{x} &= \mathbf{A}\mathbf{x} \\ (\mathbf{I}-\mathbf{A})\mathbf{x} &= \mathbf{0} \end{aligned} \tag{4.5}$$

where it is understood that the dimension of **x** and **A** has been adequately altered to accommodate the inclusion of the household sector and the other part of the final demand. This is a fully closed model, which has neither final demand nor value added [110].

The fully closed model does not allow to determine the effects of a change in final demand, because final demand does not exist. Closed model allows only to understand the effects introduced by a change in **A** on relative quantities [110] and does not allow to account for embodied contributions since Leontief inverse cannot be calculated. For this reason a standard input – output open model will be used in this analysis, trying to make endogenous only the part relating to the human labor, and making exogenous the residual final demand.

4.3.2 Goods and services required by workers

The requirements of workers in terms of goods and services are, obviously, a part of the total final demand of households and clearly, workers consume resources to sustain their work activities. For instance, a worker, who drives a car to reach the workplace, consumes primary exergy such as exergy embodied in fuel and generates an environmental impact related to emissions. If human labor is kept out of the account these environmental burdens cannot be counted.

Goods and services required by workers, although they are a part of households final demand, are difficult to assess. Households are composed by people that are workers and people who do not work. Moreover, workers do not work all the time. Neoclassical theories of labor supply state that there are two possible uses of time: labor and leisure [149]. If the aim is to determine goods and services required by workers, they are very difficult to assess since the goods and services used in leisure hours can be also used in working hours.

Since observations on leisure hours are not generally obtainable, leisure is defined as the difference between total time available and the individual's hours of work at his job [150]:

$$h_w + h_l = h_{tot} \tag{4.6}$$

where h_w represents the total hours of work, h_l the hours of leisure and h_{tot} the total time available.

Another factor to be considered is that not all the working hours have the same weight in terms of resource consumption. Workers that have a higher income level, have usually a higher consumption of goods and services. Table 4.3 shows the average monthly consumption of goods and services by professional condition.

Table 4.3: Average monthly expenditure by professional condition in € for Italy. Data by ISTAT.

	Professional condition					
Expenditure categories	entrepreneur, freelance	self employed	manager and employee	worker	retired	unemployed
average monthly expenditure	3488	2614	2953	2329	2167	1827
food and beverages	521	493	503	490	444	407
tobaccos	22	23	23	29	13	20
clothing and footwear	207	143	187	116	80	77
housing (main and secondary)	928	695	800	572	721	562
fuel and energy	166	149	137	127	135	114
furnishing	166	103	144	101	115	82
health	96	76	94	71	102	62
transport	574	421	466	405	252	225
communication	61	52	51	49	39	38
education	63	36	54	29	9	24
other goods and services	528	310	346	241	172	146

A further issue, related to the assessment of goods and services employed to provide a working hour, is the time domain. Goods and services have multi-year life, and they can be used at different times. For instance, education is a process that lasts several years and needs to be included in the account of goods and services consumed to provide a working hours. Clearly, evaluating requirements during a huge time domain needs data that are not available.

In a basic analysis, requirements of workers can be divided from requirements of households by means of time. Indeed, it is possible to divide final demand of households through the use of the concepts of leisure time and time of work:

$$f_{i\ \mathrm{workers}} = f_{i\ \mathrm{households}} \cdot \frac{h_w}{h_{tot}} \tag{4.7}$$

In eq. (4.7):

- $f_{i\ \mathrm{households}}$ is the households final demand of products of sector i
- $f_{i\ \mathrm{workers}}$ is the workers final demand of products of sector i

On the other hand, the households final demand except workers requirements will be:

$$f_{i\ \mathrm{households\ (except\ workers)}} = f_{i\ \mathrm{households}} \cdot \frac{h_l}{h_{tot}} \tag{4.8}$$

This is a simplified analysis that does not exactly take into account goods and services employed in working hours, does not distinguish different professional conditions (even if a more accurate analysis could be possible from this point of view using different final demand for each professional condition category) and restricts the time domain to the time frame considered in data related to IOTs (usually one year).

Once this distinction made, the scheme represented in fig. 4.3 can be modified to divide final demand of households except workers, and final demand of workers. The fig. 4.5 shows the new model of society: environment provides resources to economy, the latter transforms resources into goods and services and delivers them to two separate final demands: total final demand except workers and final demand of workers. The flows of goods and services were divided using eq. (4.7).

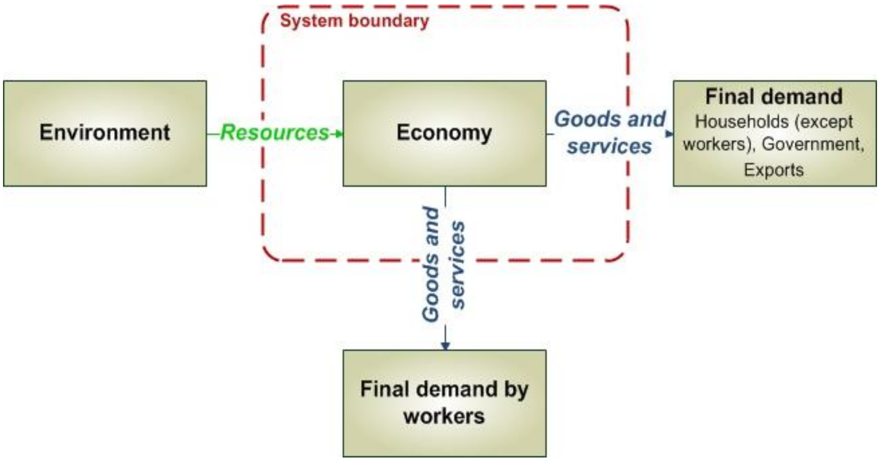

Figure 4.5: The scheme represents the flows exchanged between environment, economy, final demand except workers and final demand of workers. The system boundary divides endogenous from exogenous flows.

4.3.3 Endogenizing Human Labor in IOT

The issue concerning human labor is in the fact that it cannot be considered a part of final demand, which functions as a perfect exergy dissipater in the IO model, as already stated in paragraph 4.2.2, because human labor is also a factor of production: workers spend their resources, in terms of goods and services to enable the production of industries. Therefore, since workers exchange flows of resources from and to the economic sectors, human labor has to be regarded as endogenous in the input – output model.

The output of the new ‘labor sector’ can be measured in several ways. However in this analysis the assumption made is that human labor produces working hours to the economic sectors, since data about hours worked per sector are usually available.

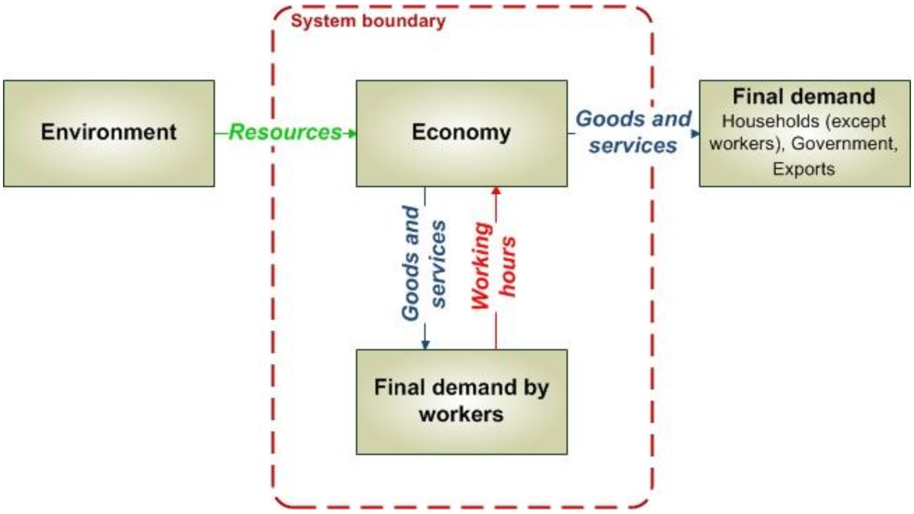

Figure 4.6: Endogenizing Human Labor in IO model. The system boundary divides endogenous from exogenous flows.

Fig. 4.6 shows that the system boundary, which divides endogenous and exogenous flows, includes human labor and the latter provides working hours to economic sectors. Fig. 4.6 is different from fig. 4.5 because the human labor interacts directly with economy, instead of being only a part of final demand.
The mathematical model can be described by means of the eq. (3.8). However, the latter has to be modified to endogenize the final demand of workers and include their output to the economic sectors:

$$\tilde{\mathbf{x}} = \begin{pmatrix} \mathbf{Z} & \mathbf{f}_{\text{workers}} \\ \mathbf{h} & 0 \end{pmatrix} \mathbf{i} + \tilde{\mathbf{f}} \tag{4.9}$$

where:

- **Z** represents the flows of money among the sectors. It is already defined in eq. (3.7). **Z** is a matrix ((n-1)×(n-1)).
- $\mathbf{f}_{\text{workers}}$ is the final demand of workers in monetary terms obtainable by eq. (4.7). $\mathbf{f}_{\text{workers}}$ is a column vector ((n-1)×1).
- **h** is the vector of the hours worked per sector, which uses hours as unit of measurement. **h** is a row vector (1×(n-1))
- **i** is the summation vector already defined in eq. (3.8). The dimension are (n×1).
- $\tilde{\mathbf{f}}$ is the total final demand minus the final demand of workers. It is both in monetary terms and in hours (relatively to the last row). $\tilde{\mathbf{f}}$ is a column vector (n×1) in hybrid units.

- $\tilde{\mathbf{x}}$ is the vector of the total production both in monetary terms and in hours (relatively to the last row). $\tilde{\mathbf{x}}$ is a column vector (n×1) in hybrid units.

Two important matters have to be discussed. Firstly, the model is in hybrid units, since both monetary terms and hours are used in the model. Hybrid units IO models are described in paragraph 3.3.7. Secondly, in eq. (4.9), the assumption made is that the 'labor sector' does not produce any flow to itself, therefore the matrix is compiled with 0 in the appropriate cell. The reason is that 'labor sector' does not need working hours for itself, but it provides working hours to other sectors of the economy.
Since the model is in hybrid units, the coefficients matrix, which is derived from the model, will be in hybrid units similarly to the coefficients matrix of the hybrid energy IOT in eq. (3.28):

$$\tilde{\mathbf{A}} = \begin{pmatrix} \frac{€}{€} & \cdots & \frac{€}{\mathrm{h}} \\ \vdots & \ddots & \vdots \\ \frac{\mathrm{h}}{€} & \cdots & \frac{\mathrm{h}}{\mathrm{h}} \end{pmatrix} \qquad (4.10)$$

Once the technical coefficients matrix are defined, the IO model can be developed in the following way:

$$\tilde{\mathbf{x}} = \tilde{\mathbf{A}}\tilde{\mathbf{x}} + \tilde{\mathbf{f}} \qquad (4.11)$$

And through the Leontief inverse matrix:

$$\tilde{\mathbf{x}} = (\mathbf{I} - \tilde{\mathbf{A}})^{-1}\tilde{\mathbf{f}} \qquad (4.12)$$

In order to evaluate the exergy costs, the diagonal matrix of exogenous inputs defined in eq. (3.22) has to be introduced:

$$\tilde{\mathbf{x}}^{\mathrm{ex}} = \tilde{\mathbf{b}}(\mathbf{I} - \tilde{\mathbf{A}})^{-1}\tilde{\mathbf{f}} \qquad (4.13)$$

where:

- $\tilde{\mathbf{b}}$ is the diagonal matrix that has been adequately altered to take into account the inclusion of the 'labor sector' and,

- $\tilde{\mathbf{x}}^{ex}$ is the vector of the total demand for exogenous inputs, with a row added to accommodate the inclusion of the labor sector.

The final demand $\tilde{\mathbf{f}}$, in the way in which it is defined in paragraph 4.2.2, does not include a demand for working hours. Nevertheless, it can be extended considering requirements for a new product that, for instance, needs working hours. The extension of the final demand can be carried out through the "the final demand approach" outlined by Miller and Blair [94] or by Joshi in EIOLCA method [113].

This model is capable of giving an exergy cost to working hours and also, is capable of enabling the account the "embodied hours" in the production chain, through the use of the hybrid units IO model. Indeed, the differences in terms of results in relation to standard IO model are: (1) a new Leontief coefficient that measures the specific exergy cost of one hour of work: it represents embodied (direct plus indirect) exergy per working hour and (2) taking into account embodied hours means giving a greater weight to the processes that make an intensive use of working hours such as services. In this manner, a higher resource consumption will allocate to the industries of the tertiary sector.

Endogenizing Human Labor in IOT: a different approach

As already stated, the output of the new 'labor sector' can be measured in several ways. Previously, working hours have been used as output of 'labor sector'. Nevertheless, the output of 'labor sector' can be also viewed as the value added (in terms of labor compensation) to the production process.

The labor compensation is measured in monetary terms and it is available directly in standard IOTs.

The model follows the same structure of eq. (4.9), but all the inter-sectorial flows are measured in monetary terms:

$$\tilde{\mathbf{x}} = \begin{pmatrix} \mathbf{Z} & \mathbf{f}_{\text{workers}} \\ \mathbf{v} & 0 \end{pmatrix} \mathbf{i} + \tilde{\mathbf{f}} \tag{4.14}$$

The row vector **v** represents the labor compensation for each economic sector. **v** is a row vector (1×(n-1)).

Since the model is not in hybrid units anymore but only in monetary terms, applying this model means that the technical coefficients matrix **A** will be compiled with the following units of measurement:

$$\tilde{\mathbf{A}} = \begin{pmatrix} \frac{€}{€} & \cdots & \frac{€}{€} \\ \vdots & \ddots & \vdots \\ \frac{€}{€} & \cdots & \frac{€}{€} \end{pmatrix} \tag{4.15}$$

The model is extended with the same previous procedure, providing eq. (4.13). The opportunities that this model can offer is in the fact that one of the results provided by the inversion of the matrix, is the specific exergy cost per euro of labor compensation. This result is more suitable for economic analysis than working hours, when data on hours worked are not easily available, whereas data on labor compensation are available.

4.4 Applications of the models

4.4.1 Example: Exergy requirements of households and Total Exergy Cost in a three-sectors economy

The example aims at determining the exergy cost of households in a three-sectors economy applying IOA, using MIOT and the diagonal matrix of the direct exergy requirements.

The mathematical model is described in eq. (3.23) and more in detail in eq.(4.3).

The implemented IO model and the relative flows of resources are illustrated in fig. 4.3.

A MIOT can contain several sectors, however for the sake of simplicity, in this example, the sectors were aggregated in the following three:

1. Primary sector: refers to the extraction of raw materials
2. Secondary sector: concerns the manufacturing of goods
3. Tertiary sector: refers to the provision of services

Table 4.4: Inter-sectorial flows, total final demand, final demand by households and total production and exogenous inputs in a three-sectors economy. Total final demand includes the households.

Three sectors economy								
	sector	*unit*	*1*	*2*	*3*	*Total final demand*	*Households final demand*	*Total production*
Primary	1	M€	2397	56302	3533	19118	9492	81352
Secondary	2	M€	12747	387602	122154	469855	123411	992360
Tertiary	3	M€	5358	119838	227781	616749	358384	969727
Exogenous inputs		ktoe	129841	0	0			

Table 4.4 shows the inter-sectorial monetary flows within the three-sectors economy, the vector of the total final demand, the vector of final demand expenditure by households, the vector of total production and the vector of exogenous inputs. The table concerning the inter-sectorial flows was implemented in the same way of the table 3.2.

The units of measurement of the flows within the economy are exclusively in M€ since this table is a MIOT. The primary exergy requirements is measured in kilotons of oil equivalent.

Once defined the MIOT, the diagonal matrix of the external resources can be formulated:

$$\mathbf{b} = \begin{pmatrix} \frac{129841\,\mathrm{kt_{oe}}}{81352\,\mathrm{M€}} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad (4.16)$$

The diagonal matrix in eq. (4.16) is compiled through eq. (3.21). The coefficients shown in the matrix represent the total external inputs from environment divided by the total production of sectors that receive the exogenous inputs. In this case, the total external input from environment is divided by the total production, in monetary terms, of primary sector, which is the only sector that extracts resources from the environment.

Once the diagonal matrix **b** and the Leontief inverse matrix **L** in monetary terms are calculated, the matrix product **bL** gives a matrix that contains the Leontief coefficients of direct and indirect exergy consumption per output of each sector or the specific exergy cost:

$$\mathbf{bL} = \begin{pmatrix} 1{,}67\frac{\mathrm{kt_{oe}}}{\mathrm{M€_1}} & 0{,}16\frac{\mathrm{kt_{oe}}}{\mathrm{M€_2}} & 0{,}03\frac{\mathrm{kt_{oe}}}{\mathrm{M€_3}} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad (4.17)$$

The subscripts in eq. (4.17) indicates that the coefficients are related to the final demand of a specific sector. Indeed, multiplying the matrix product **bL** by the households final demand $\mathbf{f}_{\mathrm{households}}$;

$$\mathbf{bLf}_{\text{households}} = \begin{pmatrix} 1{,}67\frac{\text{kt}_{\text{oe}}}{\text{M€}_1} & 0{,}16\frac{\text{kt}_{\text{oe}}}{\text{M€}_2} & 0{,}03\frac{\text{kt}_{\text{oe}}}{\text{M€}_3} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 9492\,\text{M€}_1 \\ 123411\,\text{M€}_2 \\ 358384\,\text{M€}_3 \end{pmatrix} = \tag{4.18}$$

$$= \begin{pmatrix} 1{,}67\frac{\text{kt}_{\text{oe}}}{\text{M€}_1}\cdot 9492\,\text{M€}_1 + 0{,}16\frac{\text{kt}_{\text{oe}}}{\text{M€}_2}\cdot 123411\,\text{M€}_2 + 0{,}03\frac{\text{kt}_{\text{oe}}}{\text{M€}_3}\cdot 358384\,\text{M€}_3 \\ 0 \\ 0 \end{pmatrix}$$

all the Leontief inverse coefficients are multiplied by the final demand of the specific sector to which they are related. The result is the vector $\mathbf{x}^{\text{ex}}_{\text{households}}$:

$$\mathbf{x}^{\text{ex}}_{\text{households}} = \begin{pmatrix} 48408\,\text{kt}_{\text{oe}} \\ 0 \\ 0 \end{pmatrix} \tag{4.19}$$

From eq. (4.19) it is possible to notice that only a fraction of the total direct exergy requirements is consumed by households.

The total exergy cost of every good or service can be derived also from eq.(4.18). However applying the eq. (4.4), it is possible to illustrate the consumption of primary exergy divided by classes of goods and services:

$$\mathbf{c}^{\text{ex}}_{\text{tot}} = \mathbf{bL\hat{f}}_{\text{households}} = \begin{pmatrix} 15882\,\text{kt}_{\text{oe}} & 20073\,\text{kt}_{\text{oe}} & 12453\,\text{kt}_{\text{oe}} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{4.20}$$

The matrix presents zeros in all the cells except the first row since the exogenous inputs were only associated with the primary sector.

Eq. (4.20) shows that 15882 kt_{oe} are allocated to products of the primary sector, 20073 kt_{oe} to products of the secondary sector and 12453 kt_{oe} to services of the tertiary sector. The sum of these three contributions gives the total exergy requirements of households.

In this example, the manufacturing sector is the cause of the major consumption of primary exergy relating to the households final demand.

4.4.2 Example: Exergy requirements of households and Total Exergy Cost including Labor

Referring to example 4.4.1, the novel framework, capable of including labor in IOA, will be used to calculate the exergy cost of households, specific exergy cost of goods and services and total exergy cost of goods and services. Then, the results will be compared with the results achieved in example 4.4.1.

In this model the same three sectors in example 4.4.1 will be considered and the new 'labor sector' will be included as a fourth sector. Tab. 4.5 shows the modified IOT.

Table 4.5: Inter-sectorial flows. total final demand, households final demand and total production in hybrid units model including labor sector as endogenous.

Three sectors economy and endogenous labor sector									
	sector	*unit*	*1*	*2*	*3*	*L*	*Total final demand*	*Households final demand*	*Total production*
Primary	1	M€	2397	56302	3533	803	18316	8690,1	81352
Secondary	2	M€	12747	387602	122154	10435	459420	112976	992360
Tertiary	3	M€	5358	119838	227781	30303	586446	328081	969727
Labor	L	Mh	1958	9554	20558	0	0	0	32070
Exogenous inputs		ktoe	129841	0	0	0			

In order to determine exergy cost of households, it is possible to write the following equation referring to eq. (4.13):

$$\tilde{\mathbf{x}}^{\text{ex}}_{\text{households}} = \tilde{\mathbf{b}}(\mathbf{I} - \tilde{\mathbf{A}})^{-1}\tilde{\mathbf{f}}_{\text{households (except workers)}} \tag{4.21}$$

where $\tilde{\mathbf{x}}^{\text{ex}}_{\text{households}}$ represents the demand for exogenous inputs related to the households consumption in this novel model.

Then, writing the eq. (4.21) by means of Leontief inverse matrix will return:

$$\tilde{\mathbf{x}}^{\text{ex}}_{\text{households}} = \tilde{\mathbf{b}}\tilde{\mathbf{L}}\tilde{\mathbf{f}}_{\text{households (except workers)}} \tag{4.22}$$

The matrix containing specific exergy cost $\tilde{\mathbf{b}}\tilde{\mathbf{L}}$ gives the following results:

$$\tilde{\mathbf{b}}\tilde{\mathbf{L}} = \begin{pmatrix} 1{,}68\frac{\text{ktoe}}{\text{M€}_1} & 0{,}17\frac{\text{ktoe}}{\text{M€}_2} & 0{,}04\frac{\text{ktoe}}{\text{M€}_3} & 0{,}13\frac{\text{ktoe}}{\text{Mh}} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{4.23}$$

Referring to the eq. (4.17), the specific exergy cost was increased since human labor was endogenized. A further result is the specific exergy cost related to a working hour. This result can be compared to other values provided by other methods described in paragraph 2.5.

Once the matrix containing specific exergy cost, has been found using the novel model, the exergy cost of households can be calculated as follows:

$$\tilde{\mathbf{b}}\tilde{\mathbf{L}}\tilde{\mathbf{f}}_{\text{households (except workers)}} = \begin{pmatrix} 1{,}68\frac{\text{kt}_{\text{oe}}}{\text{M€}_1} & 0{,}17\frac{\text{kt}_{\text{oe}}}{\text{M€}_2} & 0{,}04\frac{\text{kt}_{\text{oe}}}{\text{M€}_3} & 0{,}13\frac{\text{kt}_{\text{oe}}}{\text{Mh}} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 8690\,\text{M€}_1 \\ 112976\,\text{M€}_2 \\ 328081\,\text{M€}_3 \\ 0\,\text{Mh} \end{pmatrix} =$$

$$= \begin{pmatrix} 1{,}68\frac{\text{kt}_{\text{oe}}}{\text{M€}_1}\cdot 8690\,\text{M€}_1 + 0{,}17\frac{\text{kt}_{\text{oe}}}{\text{M€}_2}\cdot 112976\,\text{M€}_2 + 0{,}04\frac{\text{kt}_{\text{oe}}}{\text{M€}_3}\cdot 328081\,\text{M€}_3 + 0{,}13\frac{\text{kt}_{\text{oe}}}{\text{Mh}}\cdot 0\,\text{Mh} \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{4.24}$$

The eq. (4.24) gives the following result:

$$\tilde{\mathbf{x}}^{\text{ex}}_{\text{households}} = \begin{pmatrix} 46120\,\text{kt}_{\text{oe}} \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{4.25}$$

Therefore, using the specific exergy costs, the total exergy cost related to each economic sector can be calculated through the eq. (4.4):

$$\tilde{\mathbf{c}}^{\text{ex}}_{\text{tot}} = \tilde{\mathbf{b}}\tilde{\mathbf{L}}\hat{\tilde{\mathbf{f}}}_{\text{households (except workers)}} = \begin{pmatrix} 14575\,\text{kt}_{\text{oe}} & 18751\,\text{kt}_{\text{oe}} & 12793\,\text{kt}_{\text{oe}} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{4.26}$$

The latter equation shows that, even if the total exergy cost of households are decreased in this model, the primary exergy required by tertiary sector is increased in respect to the standard model: it has a greater relative weight on exergy consumption since embodied hours are taken into account in this model.

Example: Exergy requirements of households and Total Exergy Cost including Labor - a different approach

A different approach can be implemented to include labor as endogenous in extended IOA. The method refers to eq. (4.14), where the labor compensation is used instead of working hours as inputs towards sectors.

Table 4.6 is very close to table 4.5, although the last row in the matrix of inter-sectorial flows is replaced with values related to labor compensation.

Table 4.6: Inter-sectorial flows. total final demand, households final demand and total production, including labor sector as endogenous with labor compensation as output.

Three sectors economy and endogenous labor sector									
	sector	unit	1	2	3	L	Total final demand	Households final demand	Total production
Primary	1	M€	2397	56302	3533	803	18316	8690,1	81352
Secondary	2	M€	12747	387602	122154	10435	459420	112976	992360
Tertiary	3	M€	5358	119838	227781	30303	586446	328081	969727
Labor	L	M€	6324	130729	293779	0	0	0	430832
Exogenous inputs		ktoe	129841	0	0	0			

Once the Leontief inverse is calculated, the matrix of specific exergy costs can be written:

$$\tilde{\mathbf{b}}\tilde{\mathbf{L}} = \begin{pmatrix} 1{,}68\frac{\mathrm{kt_{oe}}}{\text{M€}_1} & 0{,}17\frac{\mathrm{kt_{oe}}}{\text{M€}_2} & 0{,}04\frac{\mathrm{kt_{oe}}}{\text{M€}_3} & 0{,}01\frac{\mathrm{kt_{oe}}}{\text{M€}_L} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{4.27}$$

As shown in eq. (4.27), specific exergy costs do not deeply change compared with the previous method, which uses working hours.

A new result achieved by this method is the specific exergy cost related to the labor compensation in monetary terms. In this way, the analysis concerning the impact of a product, can be easily carried out, if data related to labor compensation instead of working hours are available.

The exergy cost relating to households can be calculated referring to eq. (4.13):

$$\tilde{\mathbf{x}}^{\mathrm{ex}}_{\mathrm{households}} = \begin{pmatrix} 46146\ \mathrm{kt_{oe}} \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{4.28}$$

And the matrix of total exergy requirements by sector is given by eq. (4.4):

$$\tilde{\mathbf{c}}_{\text{tot}}^{\text{ex}} = \tilde{\mathbf{b}}\tilde{\mathbf{L}}\hat{\tilde{\mathbf{f}}}_{\text{households (except workers)}} = \begin{pmatrix} 14553\,\text{kt}_{\text{oe}} & 18733\,\text{kt}_{\text{oe}} & 12859\,\text{kt}_{\text{oe}} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{4.29}$$

Even though the model is substantially different the results are very similar to the model discussed in the previous section.

4.4.3 Example: Exergy cost of a new product

For illustration, considering the three-sectors economy described in previous examples. If a new product has to be introduced in the economy, some inputs are required. Table 4.7 shows the requirements of the new product in the economy. These requirements must be small enough not to affect significantly the coefficient matrix **A**. Thus, if this hypothesis is not viable, the IO model must be completely redefined.

For the sake of simplicity, since this is an illustrative example in order to only highlight the mathematical model, the vector of the final demand consists in 1's everywhere.

Table 4.7: inputs for a new product in the economy.

	sector	*unit*	$\Delta\tilde{\mathbf{f}}$
Primary	1	M€	1,0
Secondary	2	M€	1,0
Tertiary	3	M€	1,0
Labor	L	Mh	1,0

The final demand approach outlined by Miller and Blair [94] can be used to evaluate the exergy requirements of that product.

Referring to an economy in tab. 4.4, the standard IO method (with no labor sector as endogenous) gives:

$$\Delta\mathbf{x}^{\text{ex}} = \begin{pmatrix} 1{,}87\,\text{kt}_{\text{oe}} \\ 0 \\ 0 \end{pmatrix} \tag{4.30}$$

This method cannot count working hours required by the new product.

Referring to an economy in tab. 4.5, the results achieved by the model capable of including labor as endogenous sector are the following:

$$\Delta\tilde{\mathbf{x}}^{ex} = \begin{pmatrix} 2{,}01\,\mathrm{kt_{oe}} \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{4.31}$$

Comparing eq. (4.30) to eq. (4.31), it is possible to notice the potentiality of the model that includes labor sector instead of standard model.

5. Case Studies

This chapter aims at revealing and exploring the possible analysis that could be carried out with the application of the IO framework. Three case studies will be explained and analyzed, applying both the standard IO model and the previously proposed model (see Chapter 4).

The first case study concerns the comparison between three national economies: Italy, China and United States. The aim of this case study is catching the differences between the economies and between the IO models. The results will be discussed and critically analyzed.

The second case study aims to evaluate the changes in terms of exergy costs in the EU 27 economy in seven years, from 2000 to 2006. This analysis allows to extrapolate the variations sector by sector and allows the comparison between the specific exergy cost and the real market price of energetic goods.

The third case study aims at applying the method to perform a LCA analysis of a product using the final demand approach, showing the real potentialities referring to the use of the IO framework that includes labor sector as endogenous. Focusing on the economic costs related to a wind turbine and converting them in exergy costs through IO coefficients, results achieved with standard IO analysis will be compared with results reached applying the model that makes endogenous the labor sector.

By implementing these case studies, will be pointed out the possible analysis that can be carried out to choose the best policy in order to minimize the resource use, also considering the external cost relating to the labor.

Data sources for the case studies are reported in Appendix A.

Three different models will be used to evaluate the differences between them. Tab. 5.1 summarizes the IO models used in these case studies.

Table 5.1: The three models implemented in the case studies.

	Description	*Basic structure*	*Developed cost model*
Standard IO model	Labor sector not included.	$\mathbf{x} = \mathbf{Zi} + \mathbf{f}$	$\mathbf{x}^{\text{ex}} = \mathbf{b}\,(\mathbf{I} - \mathbf{A})^{-1}\mathbf{f}$
Working hours based IO model	Including Labor sector. Outputs in terms of working hours.	$\tilde{\mathbf{x}} = \begin{pmatrix} \mathbf{Z} & \mathbf{f}_{\text{workers}} \\ \mathbf{h} & 0 \end{pmatrix} \mathbf{i} + \tilde{\mathbf{f}}$	$\tilde{\mathbf{x}}^{\text{ex}} = \tilde{\mathbf{b}}(\mathbf{I} - \tilde{\mathbf{A}})^{-1}\tilde{\mathbf{f}}$
Labor compensation based IO model	Including Labor sector. Outputs in terms of labor compensation.	$\tilde{\mathbf{x}} = \begin{pmatrix} \mathbf{Z} & \mathbf{f}_{\text{workers}} \\ \mathbf{v} & 0 \end{pmatrix} \mathbf{i} + \tilde{\mathbf{f}}$	$\tilde{\mathbf{x}}^{\text{ex}} = \tilde{\mathbf{b}}(\mathbf{I} - \tilde{\mathbf{A}})^{-1}\tilde{\mathbf{f}}$

5.1 First Case Study: Comparisons among Countries

Objectives of the case study

The first case study aims to provide a comparison between three different economies: Italy, China and United States.

The structure of the national economy of these countries differs greatly from each other. In 2009 Italian GDP was equal to 2307 billion of U.S. dollars instead of 14720 billion of U.S. dollars for United States and 4520 billion of U.S. dollars for China. Furthermore, the number of individuals in population changes deeply among them and the labor policy is also totally different between these countries.

The case study is based on these differences and aims at providing a critical comparison between the exergy costs related to the provision of goods and services. The comparison will be carried out through the application of the standard IO model and the ‘working hours based IO model’, capable of endogenizing labor sector using working hours as the output of that sector.

The specific objectives of this case study are:

- Evaluate the exergy cost of one working hour in the selected countries
- Determine the specific exergy costs of goods and services
- Determine the total exergy costs of goods and services

The results related to each country will be compared among them, in order to estimate the sectors that combine to bring about the higher consumption of primary exergy, and thus, determining the exergy cost of those sectors.

Data

In order to carry out a coherent comparison, IO tables with the same structure have to be considered. All the IO tables of the selected countries must have the same unit of measurement, the same sectors and they must refer to the same year.

The IO tables used in this case study, employ the same currency (U.S. dollars) to trace the economic flows within the economy. The number of the sectors is limited to 35 and sectors are equal to each other. Moreover, all the three tables refer to the year 2009.

Tab. 5.2 illustrates the 35 sectors that have been examined in IO models for China, USA and Italy. The first two sectors refer to the primary sector, sectors in the middle refer to manufacturing sector or secondary sector, whereas the last sectors from 20 to the end, refer to the tertiary sector also known as the service sector.

Table 5.2: List of 35 sectors.

35-sectors economy

1. Agriculture, Hunting, Forestry and Fishing
2. Mining and Quarrying
3. Food, Beverages and Tobacco
4. Textiles and Textile Products
5. Leather, Leather and Footwear
6. Wood and Products of Wood and Cork
7. Pulp, Paper, Paper , Printing and Publishing
8. Coke, Refined Petroleum and Nuclear Fuel
9. Chemicals and Chemical Products
10. Rubber and Plastics
11. Other Non-Metallic Mineral
12. Basic Metals and Fabricated Metal
13. Machinery, Nec
14. Electrical and Optical Equipment
15. Transport Equipment
16. Manufacturing, Nec; Recycling
17. Electricity, Gas and Water Supply
18. Construction
19. Motor Vehicles and Motorcycles
20. Wholesale Trade and Commission Trade
21. Retail Trade
22. Hotels and Restaurants
23. Inland Transport
24. Water Transport
25. Air Transport
26. Other Supporting and Transport Activities
27. Post and Telecommunications
28. Financial Intermediation
29. Real Estate Activities
30. Renting of M&Eq and Business Activities
31. Public Admin and Defence
32. Education
33. Health and Social Work
34. Other Community Services
35. Private Households with Employed Persons

In order to compile the IO table for the ‘working hours based IO model’, data about hours worked per sector were collected and information concerning total working hours and leisure hours were derived from macro – economic social accounting, in order to split up the final demand of households. Tab. 5.3 shows data related to total population, total hours of life, total hours worked and the ratio between hours worked and total hours, which is the coefficient that is needed to divide the final demand as shown in eq. (4.7).

Table 5.3: Socio economic account for Italian, Chinese and US economies in 2009.

Hours worked and total hours for Italy, China and USA				
	Total population in thousands	Hours of life in millions	Hours worked in millions	Ratio between hours worked and total hours
Italy	60249	527781	44048	0,083
China	1334909	11693803	1555749	0,133
USA	307687	2695338	259201	0,096

The diagonal matrix of exogenous inputs is filled in using data about the TPExS of non – renewable energy resources associated with the Mining and Quarrying sector of each country, which functions as the only interface with the environment.

Data concerning TPExS of non – renewable resources are collected in tab. 5.4.

Table 5.4: Fossil fuels and nuclear fuels TPExS.

TPExS of non-renewable resources for Italy, China and USA, 2009			
	Fossil fuels TPExS in kt_{oe}	Nuclear fuels TPExS in kt_{oe}	Total in kt_{oe}
Italy	144240	0	144240
China	1962595	18277	1980872
USA	1821950	216360	2038310

Model application

The application of the IO framework is divided into steps. The first step is the implementation of the standard IO model. The procedure aimed at applying the standard model is very similar to some methodologies already discussed in chapter 3, as EIOLCA or EEIO. The monetary table, which collects the economic flows between the sectors and the final demand, is required to compute the Leontief inverse in monetary terms. Once the inverse matrix is calculated, the diagonal matrix of exogenous inputs is filled in, dividing the exogenous inputs, in terms of TPExS of non-renewable resources, by the total production in monetary terms of sectors that receive these inputs directly from the environment and function as an interface with other economic sectors. In 35-sectors economy the only sector that accomplishes this task is the Mining and Quarrying sector. Indeed, the limited degree of disaggregation does not allow to assign every non-renewable resource to their own sector, such as fossil fuels sector or nuclear fuels sector, which are aggregated in the Mining and Quarrying sector. After completing the diagonal matrix of the exogenous inputs, the latter can be multiplied by the Leontief inverse, in order to obtain the specific exergy coefficients per dollar of output for each sector. Furthermore, the eq. (4.4) can be applied to determine the total exergy cost related to every sector.

The second step is the implementation of the ‘working hours based IO model’. The 35-sectors monetary IO table of inter-industry flows is extended, adding a row and a column in order to endogenize the labor sector. The table will become a 36×36 matrix. The final demand by workers, obtained by dividing the final demand of households, is endogenized in the table through compiling the new column, which represents all the inputs required by the labor sector. The new row, which represents the outputs of the labor sector, is filled in with data concerning the hours worked per sector. Once the hybrid IO table is defined, the Leontief inverse is calculated and the diagonal matrix of the exogenous inputs is set up. Finally, specific exergy coefficients per sector, including labor sector and total exergy cost by sector can be easily evaluated as before.

Results

In order to fulfill the objectives of this case study, the specific exergy cost of one working hour, the specific exergy cost of goods and services and the total exergy cost related to every sector of the economy, have been computed for the three countries under consideration.

The specific exergy cost of one working hour is a result derived from the application of the ‘working hours based IO model’ and it is available in the matrix **bL** as described in paragraph 4.2.4, with the specific exergy costs related to other sectors.

Table 5.5: Exergy Cost of working hours for Italy, China and USA.

Exergy Cost of working hours		
	$\frac{kg_{oe}}{h_{worked}}$	$\frac{MJ}{h_{worked}}$
Italy	0,159	6.65
China	0,029	1,21
USA	0,376	15,74

Tab. 5.5 shows the exergy cost related to one working hour. USA has the higher exergy cost compared to Italy and China. On the contrary, the exergy cost of one working hour in China is about one order of magnitude less than USA and Italy, probably due to the lower demand of goods and services required by workers. Italy is in an intermediate position between the China value and USA value.

These results can be compared with the values of the GDP per capita index, that measures the wealth of the population of a nation, particularly in comparison to other nations.

Table 5.6: GDP per capita, energy use and exergy cost of working hours for Italy, China, USA, 2009

Comparison between some indicators			
	GDP per capita (current US dollars)	Energy use (kg of oil equivalent per capita)	$\frac{kg_{oe}}{h_{worked}}$
Italy	35724	2,790	0,159
China	3749	1,717	0,029
USA	46999	7,056	0,376

The results concerning the exergy cost of working hours tends to follow the values of the GDP per capita index and the energy use per capita, allowing to state that one working hour in China is less expensive compared with other countries because of the lower requirements of goods and services needed by households and, thus by workers to produce one working hour.
The exergy cost of working hours, which was computed using the IO framework, can be also compared with some values available in literature about the exergy cost of labor, such as EEA values.

Table 5.7: Comparison between results of the IO framework and the equivalent exergy of labor in EEA.

Exergy Cost in MJ per working hour		
	Values applying IO framework	***The equivalent exergy of labor in EEA***
Italy	6.65	85,33
USA	15,74	72,82

Tab. 5.7 shows the strong differences between the values provided by IO framework and values that result from the EEA method. The latter gives more weight to one working hour in Italy compared with one working hour in USA, in terms of primary exergy consumption. Nevertheless, the numeraires used in EEA method and in this IO model are totally different. Indeed, in this IO model only non-renewable resources were taken into account, whereas EEA also refer to renewable resources in the TPExS.

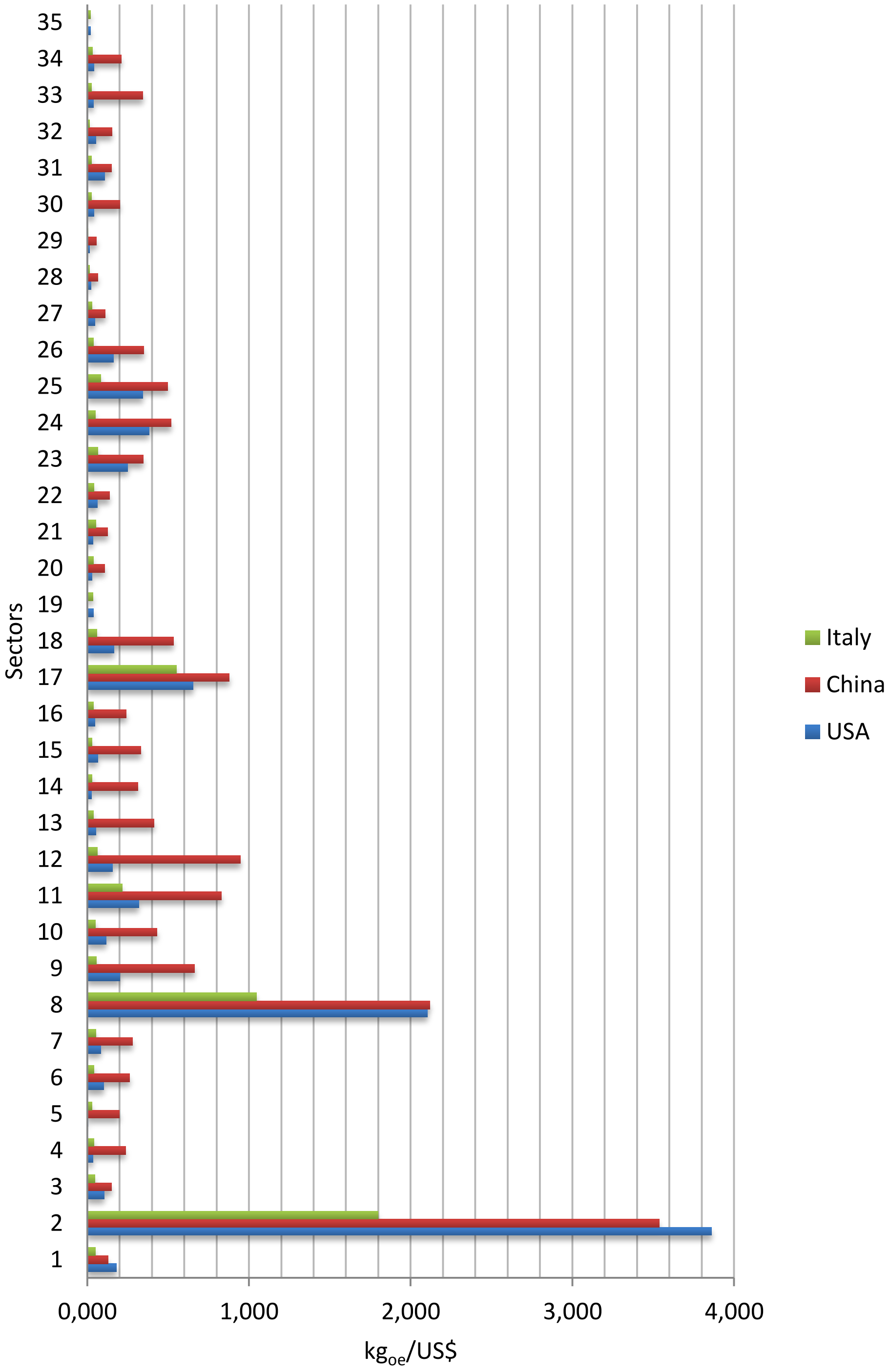

Figure 5.1: Specific exergy cost per sector for USA, China and Italy applying the IO model including working hours.

Another objective of this case study is the computation of the specific exergy cost of goods and services using the 'working hours based IO model'.

Fig. 5.1 illustrates how the IO model (both the standard IO model and the 'working hours based IO model') is capable of giving an high exergy cost to the energetic goods and services, in accordance to real values. Indeed, sector 2, which has the highest specific exergy cost, refers to 'Mining and Quarrying' sector; sector 8, which has the second highest specific exergy cost, represents the products of the sector 'Coke, Refined Petroleum and Nuclear Fuel', whereas sector 17, which has the third highest specific exergy cost, is the 'Electricity and Gas' sector.

By applying the 'working hours based IO model', the specific exergy costs change because an exergy cost is assigned to working hours. Fig. 5.2 reports the last sectors of the economy, which are related to the service sector, or tertiary sector, pointing out a higher specific exergy cost allocated to these sectors that usually require a high value of hours worked. The case of the last sector 'Private Households with Employed Persons' is meaningful since the standard IO model gives a zero amount in terms of exergy cost to that sector, instead of the IO model that takes into account the impact of the exergy consumption related to the working hours.

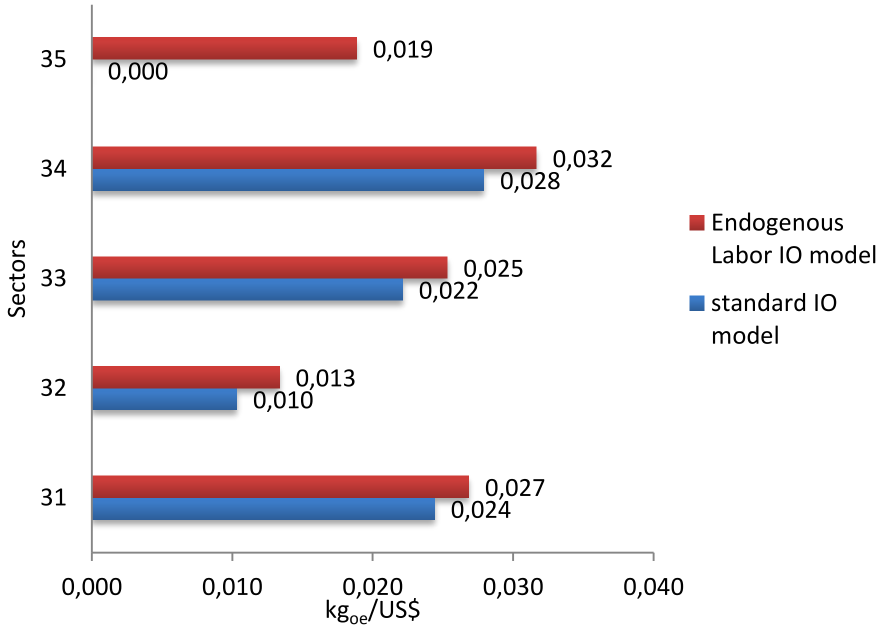

Figure 5.2: Specific exergy cost of selected services applying the standard IO model and the IO model including working hours.

Furthermore, the total exergy cost related to each sector can be evaluated for the three selected economies.

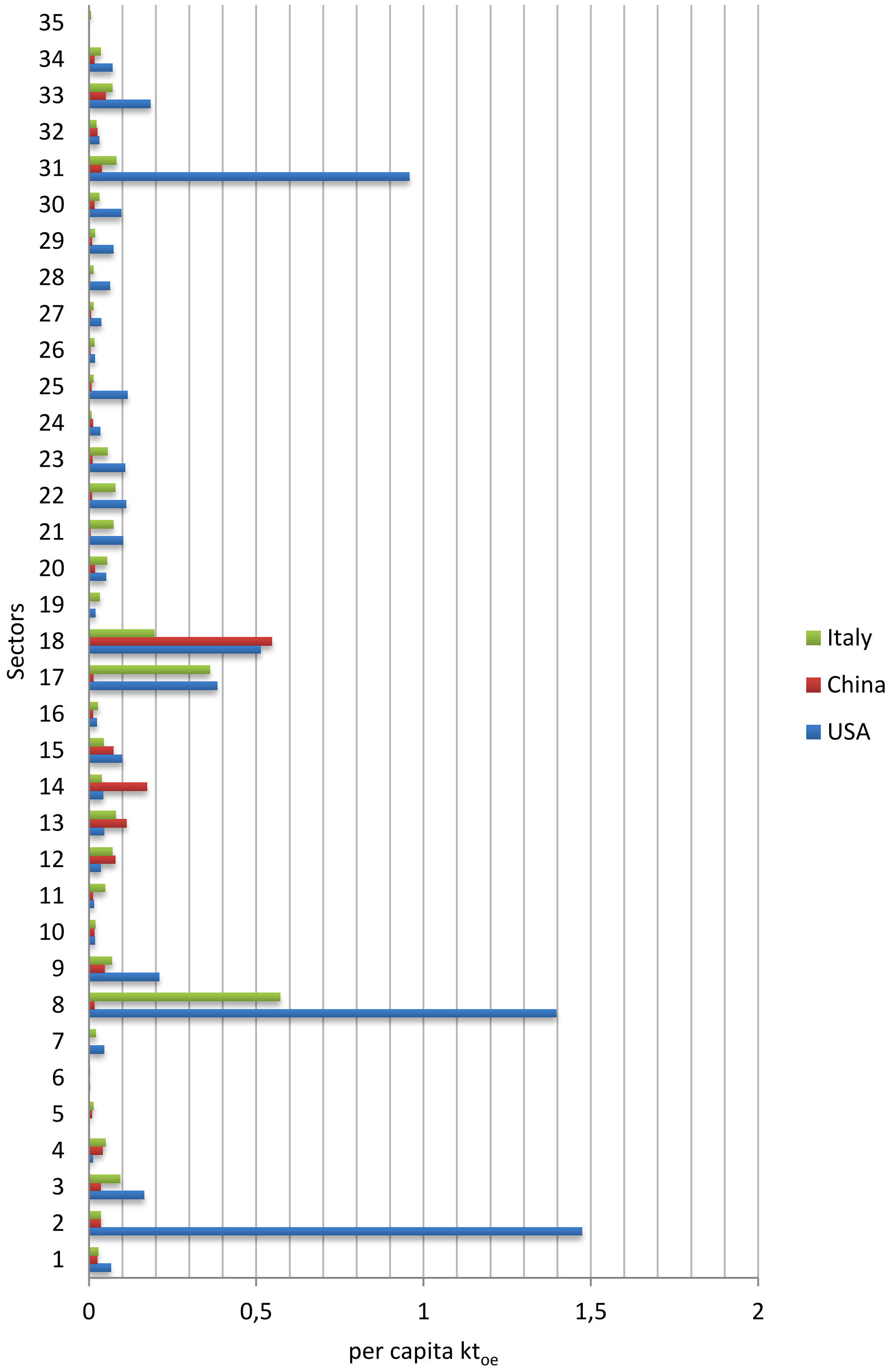

Figure 5.3: Total exergy cost per capita and per sector for USA, China and Italy applying the IO model including working hours.

Fig. 5.3 shows the total exergy cost per capita and per sector for each country. The highest total exergy costs per capita are related to the ‘Construction’ sector for China, whereas the highest total exergy costs per capita concern the ‘Mining and Quarrying’ sector, the ‘Coke, Refined Petroleum and Nuclear Fuel’ sector and the ‘Public Admin and Defence’ sector for USA. Italy presents the highest exergy costs in ‘Coke, Refined Petroleum and Nuclear Fuel’ sector and ‘Electricity and Gas’ sector.

5.2 Second Case Study: Scenario Analysis

Objectives of the case study

The second case study aims at providing a comparison among the years for a specific economy through the use of the ‘working hours based IO model’, in order to evaluate:

- the changes in the exergy cost of one working hour
- the differences between the exergy cost of energetic products and the inverse of the market price of those products
- the changes in the total exergy costs of goods and services.

The scenario analysis allows to understand the trends in the primary exergy consumption related to every sectors of the economy and allows to determine the changes in the technology for a specific sector.

Data

In this case study, the IO table is based on Euro 27 IO tables composed by 59 sectors. The IO tables are available for a range of years from 2000 to 2006.
The exogenous diagonal matrix has been composed with Eurostat data and takes into account the tons of oil equivalent in terms of fossil fuels and nuclear fuels.
In this case study, because of the high number of the sectors, assigning different types of fuels to different sectors was possible, allocating primary resources to the following sectors: ‘Coal and lignite, peat’, ‘Crude petroleum and natural gas’ and ‘Uranium and thorium ores’. The latter operate as sectors that receive the exogenous inputs from the environment and allocate the resources towards other sectors of the economy.
Table 5.6 shows the list of 59 sectors, which compose the EU 27 IOT, used in the present case study.

Table 5.8: List of 59 sectors.

59-sectors economy

1. Products of agriculture, hunting
2. Products of forestry, logging
3. Fish and other fishing products
4. Coal and lignite; peat
5. Crude petroleum and natural gas
6. Uranium and thorium ores
7. Metal ores
8. Other mining and quarrying products
9. Food products and beverages
10. Tobacco products
11. Textiles
12. Wearing apparel; furs
13. Leather and leather products
14. Wood and products of wood and cork
15. Pulp, paper and paper products
16. Printed matter and recorded media
17. Coke, refined petroleum and nuclear fuels
18. Chemicals, chemical products
19. Rubber and plastic products
20. Other non-metallic mineral products
21. Basic metals
22. Fabricated metal products
23. Machinery and equipment n.e.c.

31. Secondary raw materials
32. Electrical energy, gas, steam and hot water
33. Collected and purified water
34. Construction work
35. Trade, maintenance and repair services of motor vehicles and motorcycles
36. Wholesale trade and commission trade services
37. Retail trade services
38. Hotel and restaurant services
39. Land transport; transport via pipeline services
40. Water transport services
41. Air transport services
42. Auxiliary transport services; travel agency services
43. Post and telecommunication services
44. Financial intermediation services
45. Insurance and pension funding services
46. Services auxiliary to financial intermediation
47. Real estate services
48. Renting services of machinery and equipment
49. Computer and related services
50. Research and development services
51. Other business services
52. Public administration and defence services
53. Education services

24. Office machinery and computers
25. Electrical machinery
26. Radio, television and communication
27. Medical, precision and optical instruments
28. Motor vehicles, trailers and semi-trailers
29. Other transport equipment
30. Furniture; other manufactured goods n.e.c.
54. Health and social work services
55. Sewage and refuse disposal services, sanitation
56. Membership organisation services n.e.c.
57. Recreational, cultural and sporting services
58. Other services
59. Private households with employed persons

Data concerning total population, total hours of life and total hours worked are reported in tab. 5.9. Moreover, data related to hours worked per sector were collected.

Table 5.9: data on total population, hours of life, hours worked and ratio between hours worked and total hours from 2000 to 2006 for EU 27.

Hours worked and total hours for EU 27 from 2000 to 2006				
	Total population in thousands	Hours of life in millions	Hours worked in millions	Ratio between hours worked and total hours
2000	482460	4226353	356890	0,084
2001	483855	4238572	357218	0,084
2002	484759	4246495	353834	0,083
2003	486509	4261825	354320	0,083
2004	488403	4278415	357094	0,083
2005	490463	4296462	358950	0,084
2006	492320	4312731	363803	0,084

Model application

In order to implement the IO model which includes working hours, the 59×59 matrix of inter-industries flows was extended, adding a row and a column to endogenize the labor sector. The final demand of households is divided using data in tab. 5.9, in order to obtain the final demand of workers. The new column will be completed with the final demand of workers, whereas the new row will be filled in with data concerning hours worked per sector. Once the hybrid units 60×60 table is created, the Leontief inverse can be calculated for each table from

2000 to 2006. The inverse matrix will be pre-multiplied by the diagonal matrix of the exogenous inputs to compute the specific exergy costs of goods and services and the specific exergy cost of one working hour among the years. Subsequently, the total exergy cost of goods and services can be evaluated applying eq. (4.4).

Results

The first result refers to the exergy cost of one working hour for every year from 2000 to 2006. Fig. 5.4 shows a changeable trend of this coefficient among the years. However the specific exergy cost of one working hour tends to remain at a constant value, although the last value collapses compared with other values.

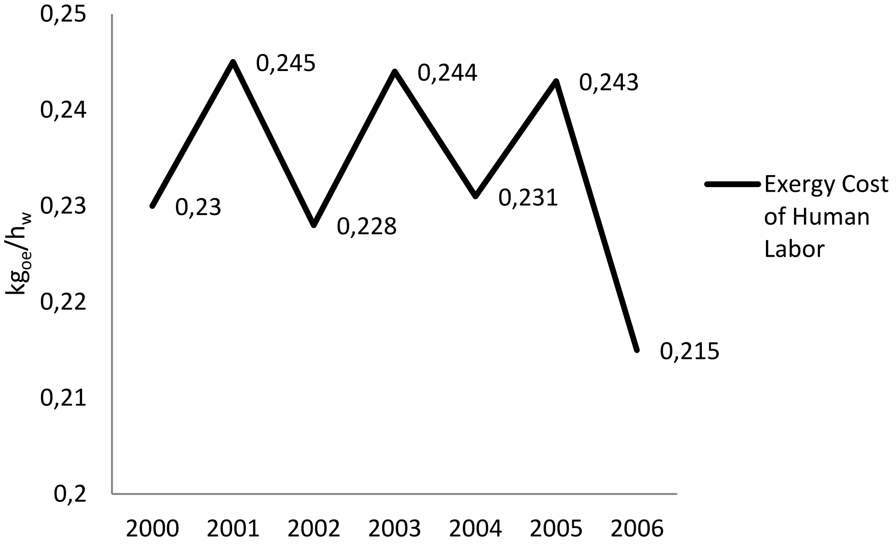

Figure 5.4: Trends of specific exergy cost of labor among the years.

Beyond this analysis it is very interesting to show the influence of embodied specific exergy cost on the real price of the energy sector products. In order to perform this analysis, data on prices of energy products are required for the years under consideration. The Eurostat database collects these data from 2000 to 2007 for the countries that belong to EU 15. In particular two products, provided by the energy sector, are taken into account: electricity and natural gas. In order to provide a coherent comparison, the inverse of the price will be calculated and reported in the same units of measurement of the exergy cost.

Fig. 5.5 illustrates the trends of the inverse of gas and electricity prices from 2001 to 2007. Specific exergy costs of energy products are calculated by means of IO framework. Indeed, the matrix of the specific exergy costs contains the exergy consumption per euro of output of the sector ‘Electrical energy, gas, steam and hot water’. Since data about IOTs refer to the end of the year instead of data on gas and electricity prices that refer to the beginning of the year, data about specific exergy costs are postponed to one year later to enable the comparison.

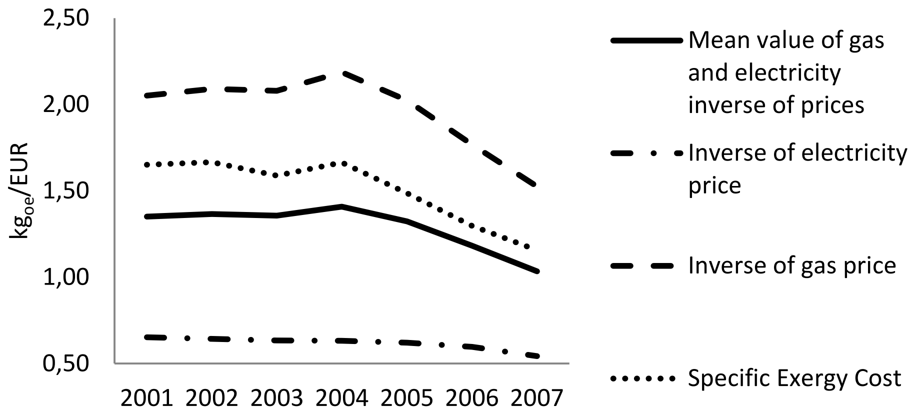

Figure 5.5: Inverse of gas and electricity prices and Specific Exergy Cost.

Furthermore, fig. 5.5 shows the trends of the specific exergy cost of energetic products compared to the inverse of the prices of natural gas and electricity. Considering the mean value, the specific exergy cost tends to follow the trend of the inverse of the mean price between electricity and natural gas.

In addition, it is possible to notice that the specific exergy cost of energetic products is always greater than the inverse of the mean value inverse price, since the specific exergy cost contains both the direct exergy and the embodied exergy that is necessary to provide the product. The distance between the two curves can represent the embodied contributions in products.

Nevertheless, this comparison depends on several factors, and it can be only an example of an analysis that can be carried out through the use of the IO framework.

The IO framework can be also used to evaluate the changes during years about technology and evolution of the processes. Applying the model that takes into account the working hours, the total exergy cost of every sector were calculated from 2000 to 2006.

During a period of seven years the total exergy cost related to each sector does not change significantly as shown in fig. 5.6. This is reasonable because technology does not change so deeply in seven years and the technical coefficient of the matrix **A** in the model, are almost constant during the years.

The consequence of this result is that it is not necessary to collect IOTs every year if they are not easily available because no more recent IOTs can be also used in the analysis.

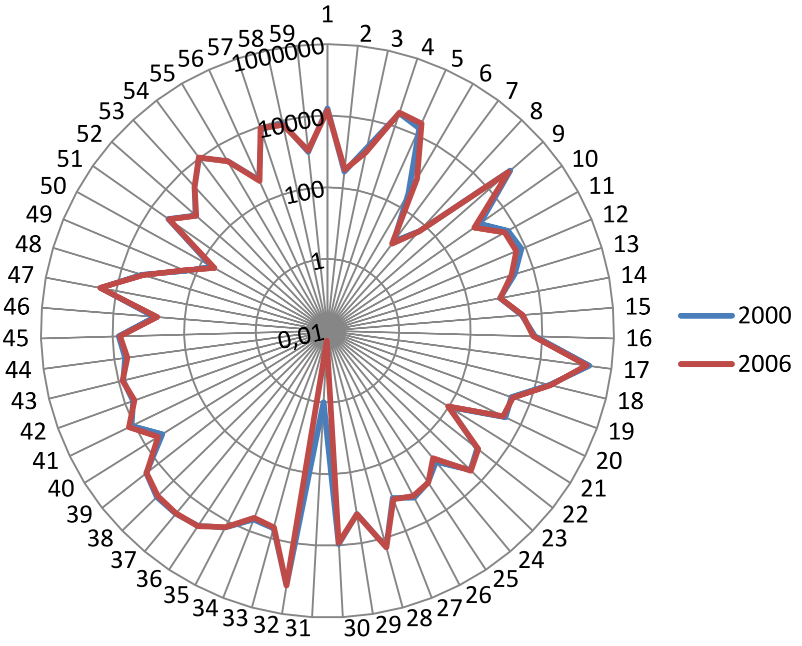

Figure 5.6: Total Exergy Cost in kt$_{oe}$ of 59 sectors for 2000 and 2006 in logarithmic scale.

5.3 Third case study: Exergy requirements of a wind turbine

Objectives of the case study

Wind turbine system reliability is a critical factor in the success of a wind energy project. Poor reliability directly affects both the project’s revenue stream through increased operation and maintenance (O&M) costs and reduced availability to generate power due to turbine downtime [151, 152].

Condition monitoring systems (CMS) could be the answer for better wind power industry maintenance management and increased reliability. Such systems are commonly used in other industries. CMS continuously monitors the performance of wind turbine parts, e.g., generator, gearbox, and transformer, and helps determine the optimal time for specific maintenance [153].

Fig. 5.7 shows the total Life Cycle Costing (LCC), with and without CMS. The investment cost for the CMS can be observed by the peak in the year 1.

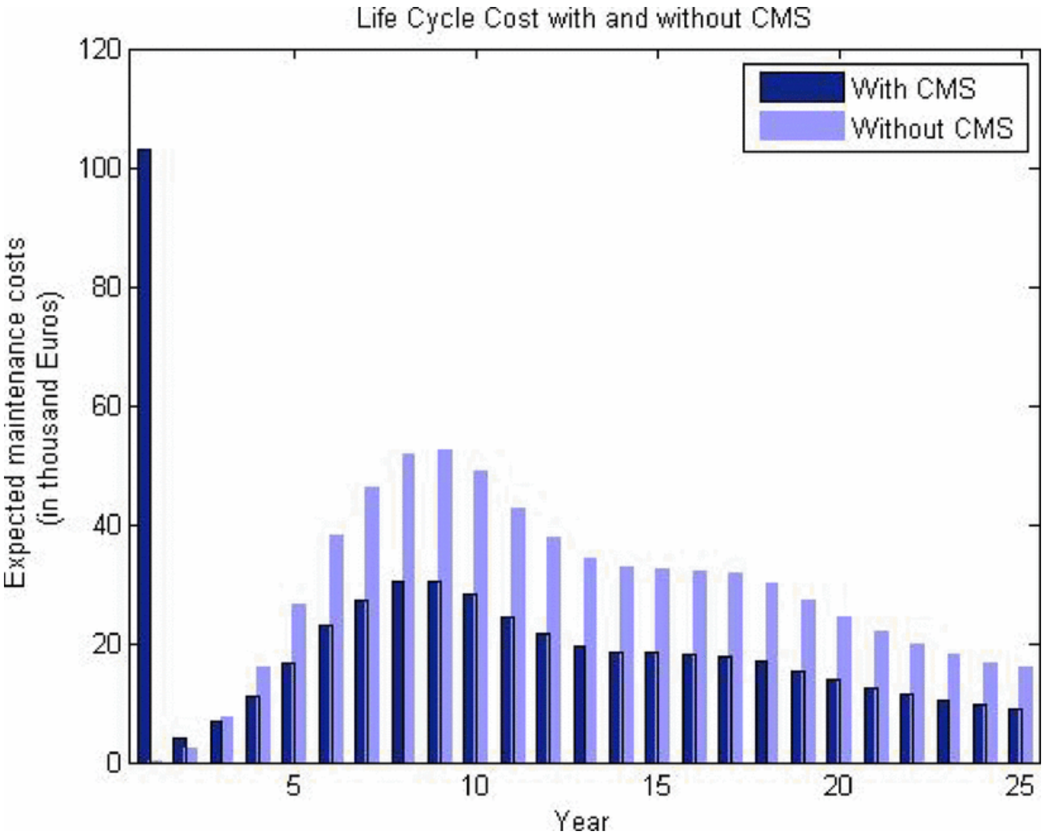

Figure 5.7: LCC with and without CMS [152].

LCC study can be converted in a LCA analysis by means of specific exergy cost coefficients, obtained by the use of the standard IO model and the ‘labor compensation based IO model’.

The aim of this study is to compare two scenarios: the first one does not use CMS, whereas the second scenario considers the use of the CMS. In addition, the case study will provide a comparison between the standard IO model and the ‘labor compensation based IO model’, in order to evaluate the potentialities of the model capable of including labor sector.

<u>Data</u>

The LCC of the two scenarios are shown in fig. 5.8 [152]. For the sake of simplicity, in this case study costs related to production loss are not taken under consideration. On the contrary, costs related to initial investment, costs for CMS, preventive maintenance and corrective maintenance are taken into account.

The turbine examined in this case study is an onshore wind turbine, 3 MW rating power and the maintenance contract establishes that the costs of maintenance are totally covered by the manufacture during the first two years of operation. The costs of preventive maintenance (PM) and corrective maintenance (CM) start from the third year of activity. Expected lifetime is 20 years.

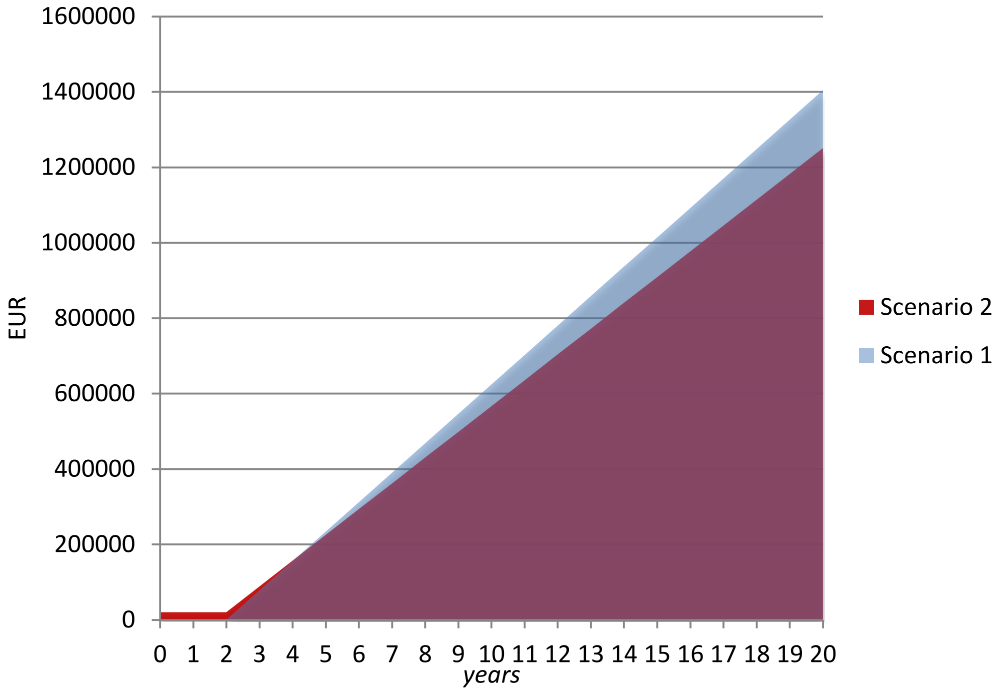

Figure 5.8: : Cumulative LCC (net of investment cost) related to a wind turbine with CMS (scenario 2) and without CMS (scenario 1).

Fig. 5.8 shows that initially, the wind turbine of the second scenario has an investment cost due to CMS. However, cumulative costs for corrective maintenance increase during the life cycle of the wind turbine without CMS, and the second scenario becomes more affordable than the first one.

Data concerning the IO model refer to EU 27 IOT for 2005. In order to perform the ‘labor compensation based IO model’, data about labor compensation, instead of hours worked, were integrated in the IOT. Data about the total hours of life and hours worked are the same of the second case study and are collected in tab. 5.9.

Model application

Firstly the IO models were implemented to compute the specific exergy cost per sector. Through the use of the ‘labor compensation based IO model’, the specific exergy cost of labor per dollar of labor compensation is also calculated.

This result is more suitable compared with exergy cost related to working hours, since all economic data of the wind turbine refer to monetary terms.

Once the specific exergy costs are calculated, the latter can be associated with every cost item related to the LCC of the wind turbine through eq. (5.1).

$$\begin{aligned} c^{ex}{}_{tot,inv} = C_{inv}(0,5 \cdot c^{ex}_{spec,\ machinery\ and\ equipment} + 0,4 \cdot c^{ex}_{spec,\ construction} + \\ + 0,1 \cdot c^{ex}_{spec,\ electrical\ machinery}) + C_{CMS} \cdot c^{ex}_{spec,\ electrical\ machinery} \end{aligned} \tag{5.1}$$

Where $c^{ex}{}_{tot,inv}$ is the total exergy cost referring to the total investment cost; C_{inv} concerns the investment cost of the wind turbine, whereas C_{CMS} concerns the investment cost related to CMS, in monetary terms. c^{ex}_{spec} refers to specific exergy of some selected sectors.

The assumptions concerning the partition of the investment costs have been made according to analysis in literature [153].

Another assumptions concerns the maintenance costs, which were directly converted into exergy costs through the specific exergy cost relating to the labor compensation.

Results

The specific exergy costs are computed using the standard IO model and the IO model capable of including labor sector. Tab. 5.10 shows the specific exergy coefficients, which were derived from the IO analysis, related to some selected sectors that provide goods and services for the production and the maintenance of the wind turbine.

Table 5.10: Specific Exergy Costs related to the goods and services that occur in the life cycle of a wind turbine – IOT: EU 27 (2005).

	Standard IO model	***Labor compensation based IO model***
	toe/k€	toe/k€
Machinery and equipment	0,111	0,119
Construction work	0,124	0,132
Electrical machinery and apparatus	0,108	0,115
Labor	-	0,015

In order to determine the total exergy cost of the wind turbine the final demand approach described in paragraph 4.4.3, or alternatively eq. (5.1) has been applied.

The results of this analysis are illustrated in fig. 5.9.

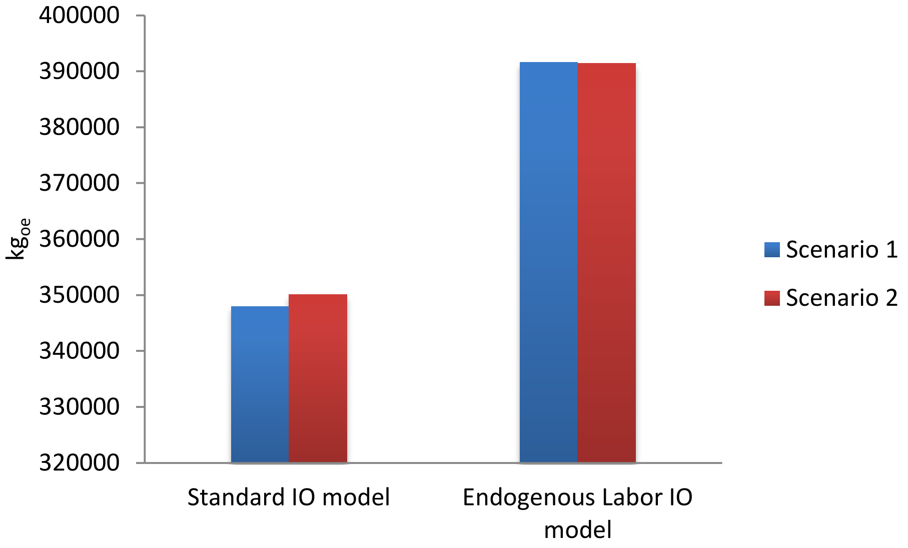

Figure 5.9: Comparison between Total Exergy Cost of a wind turbine with exergy cost of labor included, and without exergy cost of labor.

This analysis emphasizes the importance to take into account labor, since the first scenario seems to be more affordable in terms of primary exergy consumption than the second one, applying the standard IO model,. However, applying the 'labor compensation based IO model', and providing an exergy cost to the labor externality also, the first scenario becomes less suitable for minimizing exergy consumption. Moreover fig. 5.9 shows the substantial difference between the total exergy cost calculated with the standard IO model and the exergy cost derived from the IO model that includes labor sector as endogenous, and highlights the contributions that are not computed with the standard IO models, such as EIOLCA and EEIO.

In addition, in order to demonstrate the importance of including labor in the analysis, the percentage of the exergy costs of single contributions on the total exergy cost are reported in fig. 5.10. The total exergy cost related to the labor accounts for 5% and, thus cannot be neglected.

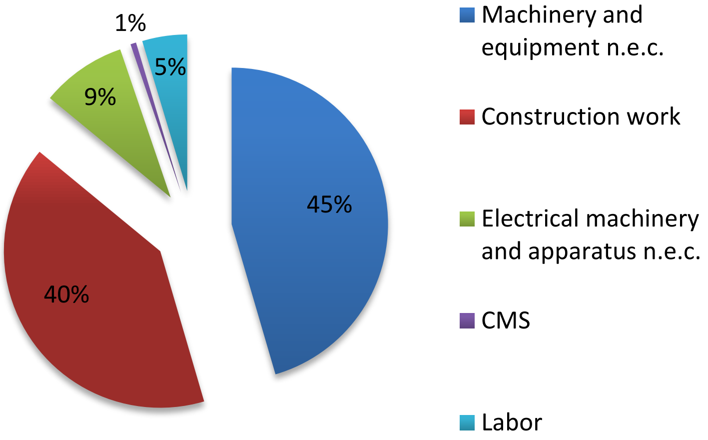

Figure 5.10: Percentages of exergy cost of single contributions on the total exergy cost.

5.4 Discussion

IO model is capable of carrying out several kinds of analysis. The three implemented case studies have demonstrated the potentialities of this framework that is suitable for:

- Evaluating the specific exergy costs and total exergy costs of goods and services for different countries,
- Performing trends analysis among the years concerning the exergy cost of goods and services,
- Providing a comparison between the market price of energetic goods and the specific exergy cost of these products,
- Calculating in a fast and simple way, the total exergy cost of new products.

Furthermore, the implementation of the IO model that endogenizes the labor sector allows to evaluate results that the standard IO model is not able to analyze. Indeed, the latter model is capable of:

- Calculating the specific exergy cost of working hours,
- Providing information about exergy cost of one working hour for different countries and among the years,
- Taking into account embodied working hours in goods and services, emphasizing the exergy consumption related to the tertiary sector,

- Evaluating the impact of human labor in terms of exergy costs in the manufacture of a new product.

Nevertheless, the drawbacks of both these approaches lie in the limitations of the IO methodology such as aggregation of data, use of monetary tables instead of physical flows, availability of data and uncertainties in the analysis.
An improvement in the collection of data and the use of hybrid method which combines process analysis and IO analysis can help in overcoming the issues relating to the basic structure of the IO methodology.

Final remarks

Sustainable development refers to environmental, economic and social sustainability. These three dimensions or pillars express themselves in the field of Industrial Ecology. Industrial Ecology aims at merging economic and ecological aspects by means of resource consumption accounting. Several numeraires have been proposed in order to account the flows of resources within human systems. In this sense, exergy has emerged as a tool capable of measuring quality of energy flows, material flows and it can be adapted to the concept of the embodied cost in goods and services. Indeed, embodied exergy can provide a measurement of exergy required in the entire life cycle of a given target product, highlighting the major causes of losses among the production and supply chain. The concept of embodied exergy is also useful to evaluate externalities as indicated in Extended Exergy Accounting (EEA), that takes into account environmental remediation costs, labor and capital externalities.

In order to determine embodied resources in goods and services, Industrial Ecology takes advantages of IOA. IOA was originally an economic tool but over the last years, it has been applied to compute environmental burdens through an extension of the methodology. Physical IOTs, extended IOTs and hybrid-units IOTs are step-forward towards the development of methods capable of tracing resource flows within an economy or a system. Furthermore, IOA allows to provide information about every product in the economy in a reproducible and fast way. Finally, IOA can be viewed as an attempt to link economics and ecology, as Daly’s idea suggests.

However, ecology and economics diverge in the treatment of well-known factors of production such as labor and capital. In particular, the human labor is an independent input in the production chain from economic point of view. On the contrary, ecology assigns an ecological cost to human labor. Moreover, Szargut demonstrates that the inclusion of the labor must be avoided in the analysis of resource consumption due to double counting. Conversely, Ayres, one of the pioneer of Industrial Ecology, claims for including labor into accounting, since workers consume goods and services, therefore primary exergy, to enable their work activities.

The aim of this work is to answer the question raised by industrial ecologists concerning the inclusion of the human labor in resource accounting. By means of IOA, the proposed model endogenizes the part related to the consumption of workers, based on the partition between working hours and leisure hours, in a way that recalls some Georgescu-Roegen’s works. In addition, endogenizing ‘labor sector’ means giving an embodied exergy content to working hours. Then, the proposed framework is capable of:

- calculating exergy cost of working hours

- distinguishing ‘labor sector’ from final demand of households in order to avoid double counting.
- calculating embodied hours (or embodied labor compensation) in the life cycle of a good or service.
- providing reproducible results, at country – level or region – level.
- providing the total and specific exergy cost of goods and services by means of simple coefficients.
- calculating the exergy cost of a new product by means of final demand approach.

Furthermore, the possible developments of this technique might concern:

- the possibility to give a different exergy content to working hours of different professional classes, by classifying the requirements of workers.
- the possibility to modify the final demand of workers, selecting in detail the goods and services that workers require.
- the use of different numeraires for calculating resource consumption, for instance, including renewable resources into accounting.
- the possibility to integrate the exergy cost of human labor resulting from this analysis, with tools such as EEA.

The development of this technique may result in solving the divergences between economics and ecology, concerning the treatment of human labor. Moreover, Industrial Ecology can benefit from this framework, by applying it in the analysis of industrial processes, emphasizing the interaction between human beings and the environment. Finally, this tool is step-forward from a sustainable point of view, since social, economic and environmental aspects, have been processed in the analysis.

Appendix A

Data sources for Case Studies

IO tables for USA, China, Italy - World Input – Output Database (WIOD)

IO tables from 2000 to 2006 for EU 27 - Eurostat Database

Data on energy balances (first case study) - International Energy Agency (IEA)

Data on energy balances (second and third case study) – Eurostat Database

Data on hours worked per sector - World Input – Output Database (WIOD)

Data on population – The World Bank Data

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