ENERGY EFFICIENT MANUFACTURING

THEORY AND APPLICATIONS

Edited by
John W. Sutherland,
David A. Dornfeld
and Barbara S. Linke

Scrivener Publishing

WILEY

Energy Efficient Manufacturing

Scrivener Publishing
100 Cummings Center, Suite 541J
Beverly, MA 01915-6106

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This edition first published 2018 by John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA and Scrivener Publishing LLC, 100 Cummings Center, Suite 541J, Beverly, MA 01915, USA

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Library of Congress Cataloging-in-Publication Data

Names: Sutherland, John W. (John William), 1958- editor. | Dornfeld, D. A., editor. | Linke, Barbara S., editor.
Title: Energy efficient manufacturing : theory and applications / edited by John W. Sutherland, David A. Dornfeld and Barbara S. Linke.
Description: Hoboken, NJ : John Wiley & Sons ; Beverly, MA : Scrivener Publishing, 2018. | Includes index. |
Identifiers: LCCN 2018010577 (print) | LCCN 2018015275 (ebook) | ISBN 9781119519812 (pdf) | ISBN 9781119521372 (epub) | ISBN 9781118423844 (cloth)
Subjects: LCSH: Manufacturing processes--Energy conservation. | Process control.
Classification: LCC TS183 (ebook) | LCC TS183 .E48 2018 (print) | DDC 658.2/6--dc23
LC record available at https://lccn.loc.gov/2018010577

Cover image: Pixabay.Com
Cover design by Russell Richardson

Set in size of 11pt and Minion Pro by Exeter Premedia Services Private Ltd., Chennai, India

Printed in the USA

10 9 8 7 6 5 4 3 2 1

Dedication

In March 2016, our good friend and mentor Professor David A. Dornfeld passed away. Dave was a constant source of inspiration and was always ready with a kind word and helpful suggestions. He was a passionate teacher and innovative researcher who made pioneering contributions to the fields of precision and sustainable manufacturing. Dave's good natured personality, irrepressible humor, and intelligence elevated every meeting and conference he attended. He was active in many societies and received numerous honors. Dave was very inclusive and promoted talent where he saw it. His legacy is the many students, post-docs, and colleagues who benefitted from his excellent support, guidance, and advice.

We will miss you Dave!

John W. Sutherland
West Lafayette, IN

Barbara S. Linke
Davis, CA

June 2018

Contents

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Introduction to Energy Efficient Manufacturing

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Abstract

Over the last decade, manufacturers around the world have expressed increasing interest in reducing their energy consumption. It appears that there are at least two principal motivations for this interest: i) the emergence of policies and legislation related to carbon emissions due to energy generation, and ii) the rising cost of energy relative to other production costs. Thus, manufacturers have begun to search for opportunities to reduce their energy usage.

A recent study by Johnson Controls shows that the demand for facility projects that promote and introduce renewable energy have dramatically increased over the last ten years [1]. Cost reduction remains the primary driver, but energy security, customer and employee attraction, greenhouse gas reduction, enhanced reputation, government policy, and investor expectations are increasingly important for investment in renewable energy [1].

In this book, the authors explore a variety of opportunities to reduce the energy footprint of manufacturing; these opportunities cover the entire spatial scale of the manufacturing enterprise: from unit process-oriented approaches to enterprise-level strategies. Each chapter examines some aspect of this spatial scale, and discusses and describes the opportunities that exist at each point on the scale. Each chapter uses one or more case studies to demonstrate how the opportunity may be acted on. Our goal is to inform students, practicing engineers, and business leaders of energy reduction approaches that exist across the manufacturing enterprise and provide some guidance on how to respond to these opportunities.

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John W. Sutherland, David A. Dornfeld and Barbara S. Linke (eds.) Energy Efficient Manufacturing, (1–10) © 2018 Scrivener Publishing LLC

Keywords: Introduction, energy consumption, energy efficiency, overview

1.1 Energy Use Implications

Energy is defined as the ability to do work. It can be neither created nor destroyed but can be changed from one form to another (First Law of Thermodynamics). The different forms of energy include kinetic, potential, heat, electric, light, chemical and nuclear. The different forms have different relevance in our daily life. The different forms of energy are such so that some conversions from one form to another are easier than others (e.g., chemical energy in oil is readily converted into heat and light through combustion, but it is difficult to convert electricity into nuclear energy, for example with particle accelerators) [2].

Worldwide we use about 500 EJ of energy per year [3]. Although energy cannot be destroyed, the useful energy decreases in most systems. In addition, theory-based energy requirements often significantly underestimate actual energy requirements. For example, reduction of iron oxide to iron theoretically requires 7.35 MJ/kg of energy, but generally consumes 20 MJ/kg in industrial practice [2]. Theoretical energy and the actual energy consumed by industry differ because of energy losses at various steps in every process. A recent DOE bandwidth study estimated the potential energy savings opportunities for the U.S. Iron and Steel Manufacturing Sector as 240 TBtu (or 256 PJ) [4]. These savings could occur if the best technologies and practices available today were used to upgrade production. The savings would be 39% of the thermodynamic minimum or the minimum amount of energy theoretically required for these processes assuming ideal conditions.

Energy use may be attributed to four principal end-uses: transportation, residential, commercial, and industrial consumption, with each end-use roughly representing one-quarter of the total U.S. consumption (please refer to Figure 1.1). Manufacturing accounts for about 90% of industrial energy consumption and 84% of energy-related CO_2 emissions (construction, mining, and agricultural activities account for the remaining industry sector contributions).

Manufacturing sector activities generate carbon dioxide and other greenhouse gas (GHG) emissions directly through onsite energy consumption (onsite generation and process energy), as well as indirectly through energy consumption to support non-process operations (e.g., facility HVAC – Heating, Ventilation and Air Conditioning, lighting, and onsite transportation). On a global scale, industry accounts for 21% of the

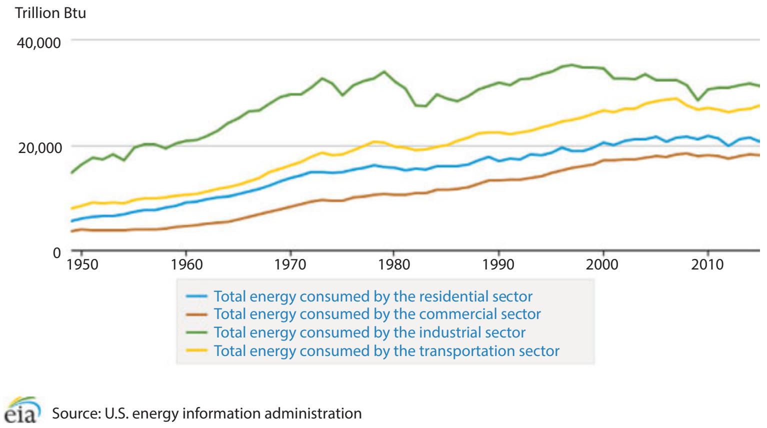

Figure 1.1 Energy consumption in the USA by sector [5].

total emissions generated [6]. Climate scientists report that these emissions upset the natural carbon balance of earth's systems [7]. As actions are demanded to reduce GHG, it should be noted that such emissions are largely proportional to energy consumption. Further, environmental impacts from electricity generation and transmission include the physical footprint of the power plant, carbon dioxide and monoxide, sulfur dioxide, nitrogen oxides, particulate matter, heavy metals, and liquid and solid wastes.

1.2 Drivers and Solutions for Energy Efficiency

Around the globe industry is facing pressure from governments in the form of regulations, penalties, or tax benefits to reduce GHG emissions. For example, the Global Warming Solutions Act of 2006 (AB32) is a California State Law to reduce GHG emissions throughout California by 2020 [8]. It applies to 6 GHG contributors: CO_2, CH_4, NO_x, hydrofluorocarbons, perfluorocarbons, and SF_6. The European Union Emissions Trading System (EU ETS) has set a cap on GHG emissions and allows trading of 'allowances' [9].

Energy prices are increasing (Figure 1.2) and using energy more efficiently is therefore in the best interest of companies and part of their continuous improvement efforts. Furthermore, depending upon an acquired resource always involves a financial risk. This includes electricity, gasoline, and natural gas. Electricity at peak hours of demand costs more than at off-peak times. In addition, companies pay a cost penalty for low power

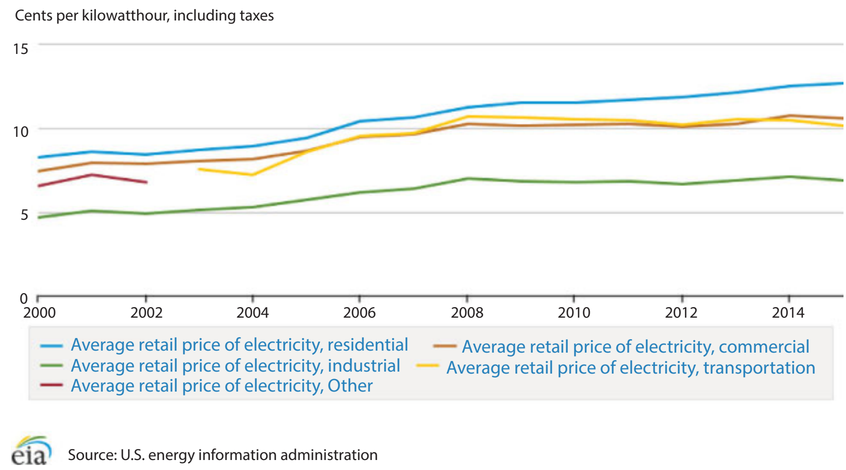

Figure 1.2 Average retail prices of electricity [5].

factors. The power factor describes the ratio between real power ("consumed" power that does useful work) and apparent power (includes added load from capacitors or inductors) in an AC electrical circuit. Since power plants have to generate enough electricity to satisfy the apparent power, industrial consumers must pay additional costs for low power factors.

In addition to pressure from governmental regulations and energy prices, companies are always striving to increase their competitiveness and enhance their market share. Growing pressure from society, consumers, and customers to become greener and more environmentally-friendly also drives manufacturers to reduce energy usage.

The U.S. Department of Energy has initiated many initiatives to help American companies become leaders in the use and production of clean energy technologies like electric vehicles, LED bulbs, and solar panels and to increase their energy productivity (output per unit of energy input) by implementing energy efficiency measures. Manufacturing data is key to achieving higher energy efficiency. For example, smart manufacturing, which is receiving increasing attention, seeks to use data from ubiquitous sensors across the manufacturing enterprise to increase throughput, improve quality, and reduce environmental impacts.

Dornfeld and Wright suggested that rather than implementing one solution, that "technology wedges" should be adopted to offer a better framework for addressing the manufacturing energy challenge [10]. "Technology wedges" are the manufacturing equivalent of the "stabilization wedges" concept introduced by Pacala and Socolow [11]. Stabilization wedges can reduce GHG through efficient cars, efficient buildings, wind power instead of coal power, reinventing land use rather than deforesting, etc. – in short, employing alternative technologies to reduce fossil fuel consumption through demand-side (consumptive) technology and supply-side (generative) technology changes. Both concepts highlight the gap between the current trends in consumption rate with respect to fossil fuel consumption/emission and movement towards a sustainable rate with respect to the atmosphere`s capability to accommodate emissions [10]. Instead of seeking a single solution to fill this gap, smaller wedges, such as simpler, single technologies should be introduced to reduce consumption rates. Manufacturing engineers have the power to embed technology wedges in their processes, manufacturing equipment, factories, business operations, and supply chains. This book explores some technology wedges for energy reduction.

Overview of the Book Contents

This book presents a variety of opportunities to reduce the energy footprint of manufacturing, mainly for discrete product manufacturing. These opportunities cover the entire spatial scale of the manufacturing enterprise: from unit process-oriented approaches to enterprise-level strategies. Each chapter examines some aspect of this spatial scale, and discusses and describes the opportunities that exist at that level (Figure 1.3). The book is therefore divided into three sections:

Section I. Manufacturing Processes
In order to identify, analyze, and improve energy efficiencies, an enterprise must have a clear understanding of the performance of its manufacturing processes and the effect of process parameters on the energy consumption of unit processes. The primary focus of this section is therefore on the energy consumed by unit processes, explained by the physical principles associated with each process. Each chapter in this section will describe the physics of the manufacturing process and how energy is utilized, discuss energy reduction opportunities, and present a case study.

Chapter 2 lays the ground work for explaining the terminology for this book, in particular power, energy, and work. The energy for a unit manufacturing process is classified into four parts: processing, machine tool, process peripherals, and background. Processing energy can be modeled using a first principles approach, which will be demonstrated with examples from forging, orthogonal cutting, and grinding.

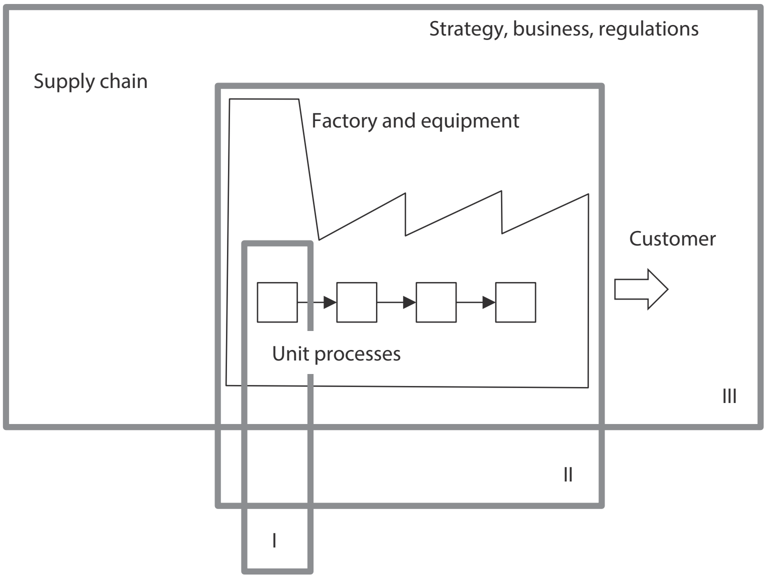

Figure 1.3 Structure of the book.

Chapter 3 focuses on raw material processing, which remains one of the most energy intensive phases in the product life cycle. This chapter provides an overview of the steel, aluminum, titanium, and polymer industries and describes the related materials processing technologies.

Chapter 4 discusses deformation processes, in particular the general concept, geometric accuracy, surface finish, formability prediction, and energy consumption of incremental forming in comparison with conventional forming. Surface texturing is introduced as a strategy to save energy by reducing friction at moving interfaces.

Chapter 5 reviews machining processes and the energy for machine tools and machining lines, discusses how energy depends on the material removal rate, and gives strategies for process optimization with regard to energy consumption. A detailed case study illustrates the optimization for minimal energy consumption in a turning process. Further studies address power consumption in turning, milling, drilling and grinding processes.

Chapter 6 concentrates on nontraditional machining processes, in particular electro-discharge machining (EDM), electrochemical machining (ECM), electrochemical discharge machining (ECDM), and electrochemical grinding (ECG). The electrical energy requirements herein are of significant importance as electrical energy is controlling the material removal in these processes.

Chapter 7 describes the principles and energy requirements for many of the most important surface treatment and coating processes. The surface treatment processes include hardening and heat treatment with furnaces, as well as laser and electron beam operations. Coating principles are discussed for thermal spraying, hard facing, physical and chemical vapor deposition, as well as certain electroplating operations. In addition, texturing with energy beams and through surface replication and machining are introduced, as are the stress-inducing operations of peening, burnishing, and explosive hardening.

Chapter 8 focuses on joining processes, which play a prominent role in manufacturing since almost all products are fabricated from multiple parts. Fusion welding processes, solid state welding, chemical joining, and mechanical joining methods are discussed. For the equipment and processes, models for energy efficiency and example data are given. Furthermore, the efficiency of joining facilities such as welding shops is analyzed and applied to case studies.

Section II. Manufacturing Systems and Enterprises

Careful consideration must be given not only to the energy consumed by manufacturing operations but also to the energy consumed by the auxiliary equipment of a manufacturing system as well as the other system elements that may influence the technical and economic performance of the system. The focus of this section is on reducing energy consumption at the facilities level, and improving the collective energy efficiency of the equipment in a facility.

Chapter 9 characterizes the energy consumption of production equipment. For this, power measurement is described, followed by the power breakdown of common manufacturing equipment. A life cycle energy analysis of equipment with the example of two milling machines is presented. Multiple energy reduction strategies and their additional life cycle impacts are discussed.

Chapter 10 introduces assembly processes and methods and their energy consumption. Energy consumption analyses have the potential to influence assembly workstation design, material handling, and part location, as well as upstream fastener design or selection decisions.

Chapter 11 investigates supporting facilities such as lighting, HVAC, compressed air, pumps, process heating, cooling, and cleaning with regard to their electricity use and energy efficiency. Several strategies for industrial lighting are presented including more efficient lamp technologies, occupancy sensors, and reduced lighting levels. Furthermore, strategies for higher efficiency HVAC and air compressors are introduced, followed by energy management benefits and approaches.

Chapter 12 focuses on process planning, which determines the specific and sequence of manufacturing operations needed to produce a given part with the design specifications. The basic concepts and procedures of process planning and an energy efficient approach are introduced that is based on energy and carbon footprint models, feature-based technology, and genetic algorithms. For a case study, the energy efficient process plan is compared with a cost-driven process plan.

Chapter 13 explores scheduling, the act of allocating limited resources to tasks over time. Traditionally, scheduling is addressed with time-based objectives, such as minimizing the total waiting time. This chapter presents an approach that also addresses energy. The mathematics are explained and optimization models demonstrated.

Section III. Beyond the Factory

Manufacturing is often considered to consist of the processes and systems used to produce products. Other business organizational elements can, however, either impede or promote efforts directed at reducing the energy consumption of manufacturing, and more generally, the energy consumed by the enterprise and society. With this in mind, this section examines a variety of system-oriented opportunities for reducing energy consumption.

In Chapter 14, supply chain management is used to explore energy consumption along the supply chain. The supply chain can be described as the network of companies working together to provide goods or services to an end-use customer. The supply chain structure in horizontal and vertical dimensions, business relationships, and main activities (customer and supplier relationship management, customer service management, order fulfillment, etc.) are explored with regard to energy use.

Drivers and barriers for companies for implementing energy efficient projects are tackled in Chapter 15. They provide the reference for a proposed framework for project selection. Different efficiency opportunities ranging from lighting, efficient HVAC systems, improved motor systems, and building envelope projects are presented.

Chapter 16 explores the imperatives of efficiency (doing things right) and effectiveness (doing the right thing) with regard to energy. The strategies for higher energy efficiency explained in this book often have well delineated objectives. Energy effectiveness, however, depends highly on the decision-maker's viewpoint. One strategy for considering both imperatives is to constantly pursue energy efficiency improvements, and to periodically adopt a course correction with energy effectiveness in mind.

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Operation Planning & Monitoring

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Abstract
Manufacturing industry is energy intensive. Due to the increasing energy cost and upcoming energy and environmental regulations, manufacturing faces the challenge of improving energy efficiency. This chapter gives an overall review of energy consumption in various manufacturing processes. The basic concepts of power, energy, and work are introduced. The scope and boundary of energy accounting are also discussed. The energy for a unit manufacturing process is classified into four parts: processing energy, machine tool energy, process periphery energy, and background energy. Case studies on processing energy modeling in forging, orthogonal cutting, grinding has been provided. The relationship between specific energy and material removal rate has been investigated. In addition, the measurement of power and energy consumption in manufacturing is discussed. Furthermore, possible energy reduction strategies are discussed.

Keywords: Manufacturing, energy consumption, energy efficiency, sustainability

2.1 Unit Manufacturing Processes

Manufacturing involves the controlled application of energy to convert raw materials into finished products with defined shape, structure, and properties that satisfy given functions. The energy applied during processing may be mechanical, thermal, electrical, or chemical in nature. Usually manufacturing entails a process chain through the sequencing of different processes. The terminology “process” is equivalent to “operation.” They are

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the individual steps required to produce finished goods by transforming raw material and adding value to the workpiece as it becomes a finished product. Each individual process is known as a "unit operation/process." These unit processes can be considered as the fundamental building blocks of a nation's manufacturing capability. For example, a modern process chain to manufacture bearings is shown in Figure 2.1. The individual process such as forming, hardening, hard turning, and polishing is referred as unit process [1].

From the viewpoint of input and output, a unit process may be defined as an area of the process or a piece of equipment where materials are input, a function occurs and materials are output, possibly in a different form, state or composition [2–4]. All manufacturing processes take material inputs, including working materials and auxiliary materials, and transform them into products and wastes. Similarly, the energy inputs into these processes (primarily from electricity) are transformed into useful work, some of which is embodied into the form and composition of the products and wastes, and waste heat. In addition, the energy inputs usually require fuels and produce emissions. For electrical energy inputs, this occurs at the power station. A manufacturing process, along with material and energy flows to and from the process, is diagrammed in Figure 2.2.

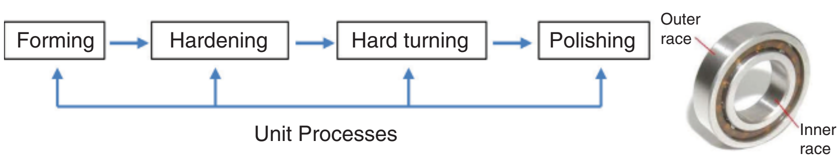

Figure 2.1 Process chain of unit processes to manufacture bearing race.

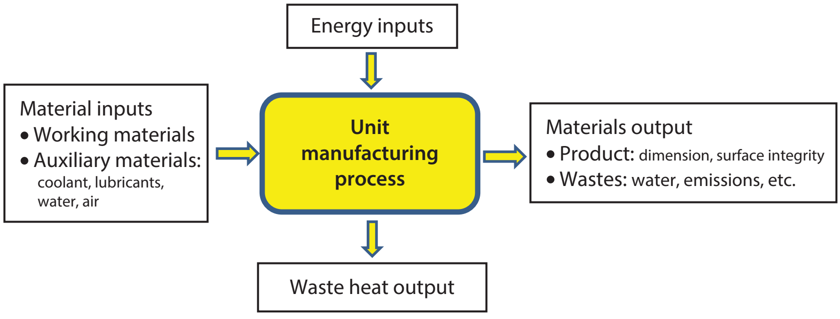

Figure 2.2 Energy and material inputs and outputs for unit manufacturing process.

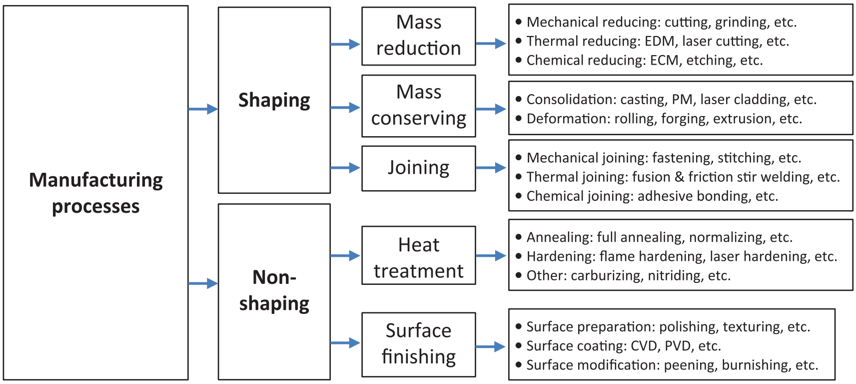

Figure 2.3 Taxonomy of manufacturing processes.

An extensive and continuously expanding variety of manufacturing processes are used to produce parts and there is usually more than one method of manufacturing a part from a given material. The taxonomy of manufacturing processes is illustrated by several versions [2, 5–7], Figure 2.3. These taxonomies have a first level classification of 5 to 6 groups and then these groups are populated by the actual different 120 unit processes.

Even though these unit manufacturing processes are very diverse, they all possess four key operation elements: the work material, the applied energy (mechanical, thermal, or chemical), a localized interaction zone between applied energy/work material, and the process equipment that provides the controlled application of energy. Advances in unit processes can be targeted at any one, or all, of these elements, although usually all four are affected to some extent by a change in any one of the elements. Furthermore, the emerging hybrid manufacturing processes may combine different unit processes working simultaneously on the same work zone within the material to improve manufacturing flexibility and efficiency. Thus, a systems approach is required for improving existing unit processes for developing new ones.

2.2 Life Cycle Inventory (LCI) of Unit Manufacturing Process

Based on a systematic taxonomy of manufacturing unit processes, a worldwide data collection effort is proposed within the CO_2PE! UPLCI-initiative. The CO_2PE!-Initiative [8] has as an objective to coordinate international efforts aiming to document and analyze the environmental impacts of a wide range of current and emerging manufacturing processes, and to provide guidelines to reduce these impacts. Figure 2.4 gives an overview of the CO_2PE UPLCI—framework to collect, document and provide LCI data for a wide range of discrete manufacturing unit processes as well as to identify the potential for environmental improvements of the involved machine tools.

As shown in Figure 2.4, this data collection can be performed in two different ways and includes an energy, resource and process emission study. The screening approach relies on representative, publicly available data and engineering calculations for energy use, material loss, and identification of variables for improvement, while the in-depth approach is subdivided into four modules, including a time study, a power consumption study, a consumables study and an emissions study, in which all relevant process inputs and outputs are measured and analyzed in detail. The screening approach provides the first insight in the unit process and results in a set of approximate LCI data, which also serve to guide the more detailed and complete in-depth approach leading to more accurate LCI data as well as the identification of potential for energy and resource efficiency improvements of the manufacturing unit process.

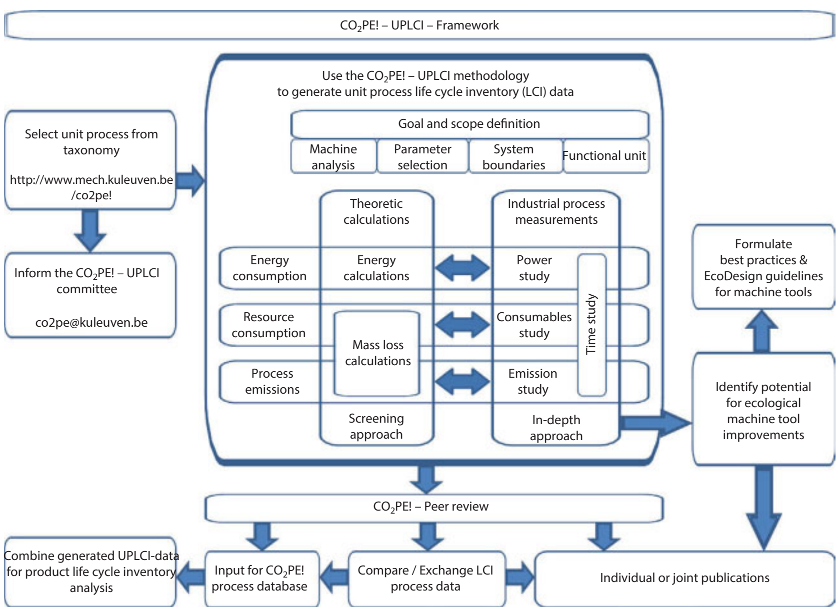

Figure 2.4 Overview of the CO_2PE! UPLCI—framework [9].