CIRP Annals - Manufacturing Technology 61 (2012) 587–609

Contents lists available at SciVerse ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

# Towards energy and resource efficient manufacturing: A processes and systems approach

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ARTICLE INFO

*Keywords:*
Energy efficiency
Manufacturing
Sustainable development

ABSTRACT

This paper aims to provide a systematic overview of the state of the art in energy and resource efficiency increasing methods and techniques in the domain of discrete part manufacturing, with attention for the effectiveness of the available options. For this purpose a structured approach, distinguishing different system scale levels, is applied: starting from a unit process focus, respectively the multi-machine, factory, multi-facility and supply chain levels are covered. Determined by the research contributions reported in literature, the de facto focus of the paper is mainly on energy related aspects of manufacturing. Significant opportunities for systematic efficiency improving measures are identified and summarized in this area.



## 1. Introduction

Manufacturing plays an indispensible role within the global economy. Not only does manufacturing provide the goods needed by consumers and industries worldwide, it also accounts for a significant portion of the employment, community presence, and economic strength. The industry sectors (including mining, manufacturing, and construction) account for nearly one-quarter of all jobs globally, with over 650 million individuals employed in the sectors [201]. Job growth within the industry sectors has been vibrant over the last decade, especially in the developing world, with 130 million industry jobs created between 1999 and 2009 as supply chains have become increasingly globalized [96,201]. While manufacturing employment within industrialized countries has remained at best flat over the last few decades, the productivity of the sector underwent extraordinary growth; for example, between 1980 and 2005, the annual global production of aluminum more than doubled from 15.4 Tg to 37.3 Tg [207]. Given its importance in terms of employment and wealth creation (in 2007, industry constituted approximately 20% of the GDP of the OECD countries [147]), manufacturing will continue to play a vital role in the global economy. Unfortunately, manufacturing also must accept responsibility for placing increasing pressure on the environment.

Industrial activity, and in particular the manufacturing sector, has a large environmental burden associated with it. Manufacturing consumes both renewable and non-renewable materials (e.g. metals, fossil oil-derived materials, and water) as well as significant amounts of energy, resulting in substantial stress on the environment. Manufacturing also releases solid, liquid, and gaseous waste streams that can result in damage to the environment.

### 1.1. Scope

While all the resources consumed and wastes produced by manufacturing affect the environment to a greater or lesser extent, the focus of the present work is on the efficient and effective utilization of resources, and in particular energy resources.

To illustrate the importance of industry with respect to the energy demand, consider, for example, the amount of energy associated with the four principal end-uses: residential, commercial, industrial, and transportation. Residential, commercial, and transportation energy consumption represent 14%, 7%, and 27% of the global total, with industrial usage constituting the balance (51%) [204]. While these percentages change from country to country, and notably from developing to industrialized nations (in 2007 the energy consumed by non-OECD countries exceeded that of the OECD countries for the first time), the sheer size of industrial energy consumption (250 quadrillion BTU or 264 EJ in 2007) suggests that this is an issue of importance [204]. Manufacturing activities dominate industrial energy consumption; Schipper [174] reports that manufacturing is responsible for 84% of energy-related industry $CO_2$ emissions and 90% of industry energy consumption.

Sizeable energy consumers, and consequently large $CO_2$ emitters, within the manufacturing sector include petroleum refining, primary metals processing, non-metallic minerals

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0007-8506/$ – see front matter © 2012 CIRP.
http://dx.doi.org/10.1016/j.cirp.2012.05.002

processing, chemical production, and paper products manufacturing. These sectors are characterized by semi-continuous processes, for which material and energy demands form major cost factors. The efficiency of these processes has received significant attention as an optimization objective in both academic and industrial research environments for many years. This is somewhat different in the sectors focused on discrete part and product manufacturing, where attention became visible mainly over the last decade. This paper is therefore predominantly focused on the industrial sectors active in discrete part/product manufacturing. Until recently, companies in these sectors investing in new machine tools primarily took functional performance and investment cost into account as selection criteria.

Perhaps driven by concerns related to environmental sustainability, a trend towards more environmentally benign manufacturing can be observed today. In addition to more stringent regulations (e.g. emission standards, worker exposure standards, and banned materials), additional motivating factors to switch to more environmentally benign manufacturing solutions include competitive economic advantages (e.g. conservation of energy, water, and materials, and reduced waste treatment and disposal costs) and proactive green behavior (e.g. corporate image, ISO 14001 certification [97], and eco-labeling) [68].

Discrete part manufacturing industries emit $CO_2$ indirectly through the consumption of electricity and directly through plant-based use of fossil fuels. It is becoming increasingly apparent that manufacturers play a critical, multi-faceted role in dictating the material and energy resources in modern society. Not only do the processes designed and employed directly by manufacturers have a sizable environmental impact, but the product design decisions made by manufacturers also control the energy and resource intensive production of materials and chemicals and the energy and resources consumed by products across their life cycle. Moreover, as supply chains become more globalized, energy intensive operations are increasingly being outsourced to developing nations that often utilize more $CO_2$ intensive energy resources.

### 1.2. Objective

The environmental challenges that we face in the near future are significant, and every part of society must proactively respond, including manufacturing. Opportunities exist across the manufacturing enterprise for more efficient usage of energy and material resources, and in particular improved material utilization. The scope of opportunities ranges from the process to the factory level to the entire enterprise, and this paper will present research efforts that cover this scope, although attention will be limited to discrete part manufacturing processes and systems.

To support the design and realization of products and their subsequent distribution, utilization, and disposition, some environment-oriented software tools have been developed, e.g. life cycle assessment software. Unfortunately, manufacturing data in support of such software tools are often not available, not representative of the situations faced by manufacturers, or based on unrealistic assumptions. With this in mind, this paper will also begin to address this deficiency.

This paper has the ambition to provide a state of the art assessment of the methodologies and technologies that can be called upon at different levels within the production system to contribute to a significant impact reduction. Perhaps owing to climate change, energy independence, and energy cost concerns, recent research work by many researchers has focused on energy-related issues. Thus, the paper has a strong focus on energy-related efforts. However, other resource streams are also covered. These, of course, also represent indirect energy consumption through embodied energy, but also have other associated wide ranging environmental effects in their production and end-of-life (EOL) treatment stages.

### 1.3. Resource efficient and effective manufacturing

This contribution addresses both the efficiency and effectiveness with which we use energy and material resources, and some brief explanation of the distinction between efficiency and effectiveness is warranted. *Efficiency* refers to the amount of resources required to produce a given level of output, where it is to be understood that it is desirable to minimize the amount of resources to achieve a given output level. *Effectiveness* is focused on making wise choices with respect to how resources are used. To illustrate the difference between efficiency and effectiveness, consider the energy consumed in a grinding operation. Efficiency improvements might include changing the wheel type or employing a different cutting fluid in order to reduce the energy required for a given operation. An effectiveness approach might change the process plan entirely to use a dramatically smaller amount of energy, with the resulting process plan not needing the grinding operation. In short, efficiency is doing things right, and effectiveness is doing the right things.

### 1.4. Manufacturing system organization

From the perspective of the organization of the system, manufacturing activities can be considered as being composed of multiple levels, from the level of the individual devices where unit processes take place, through to that of the enterprise, incorporating all the activities in the manufacturing system, including supply chain externalities [165]. In the context of this paper five levels are distinguished:

- *Device/unit process*: Individual device or machine tool in the manufacturing system, which is performing a unit process. Support equipment of the unit process is included here, such as gage systems and device level oil-circulating systems.
- *Line/cell/multi-machine system*: Logical organization of devices in the system that are acting in series or parallel to execute a specific activity (such as manufacturing a part or assembly). Support equipment for the collection of devices is included here, such as chip conveyers and tool cribs.
- *Facility*: Distinct physical entity housing multiple devices, which may or may not be logically organized into lines, cells, etc. Support equipment required at the facility level are also included here, such as power generators, water purifiers, and HVAC systems.
- *Multi-factory system*: Different facilities whose proximity to one another allows them to make use of possible synergies in terms of reuse of waste and lost energy streams.
- *Enterprise/global supply chain*: The entire manufacturing system, consisting of all the individual facilities, the infrastructure required to support the facilities, as well as the transportation and supply chain externalities.

### 1.5. Paper overview

Depending on the scale of the considered system, different strategies can be applied to optimize efficiency and effectiveness of manufacturing systems. In order to offer a systematic review of perceived opportunities and tested strategies, the paper is structured according to an increasing system scale, largely corresponding to the levels distinguished above.

In Section 2, the individual process level is studied. The material–process interaction, as achieved by stand-alone machine tools performing individual operations or a series of operations on a workpiece, is the focus. The unit processes studied in this section form the smallest building blocks for the composition of manufacturing systems. Choice of process principle and machine tool selection are typical measures that can be considered at this level. For machine tool designers, component selection and optimized control of subsystems offer opportunities.

Possible interactions and synergies between different machine tools are considered in Section 3. Multi-machine ecosystems can allow reuse of energy and material flows through proper planning and control.

Section 4 focuses on spatial and temporal considerations at factory level. Energy management aspects linked to production planning and the influence of factory layout, support facilities and building technology on plant performance are reviewed here.

Wherever considerable energy and material waste flows cannot be resolved at an in-house scale, industrial symbiosis among different manufacturing facilities can provide opportunities, as studied in Section 5.

In a globalized economy, supply chain decisions can have significant consequences in terms of required transport efforts and the nature of local supplies of energy and other resources. The sensitivity of the environmental impact of manufacturing for these factors is analyzed in Section 6.

In order to provide the reader with a realistic view of the magnitude of the energy and resource efficiency affecting measures at the respective scale levels, examples and quantified effects are reported in the different sections. While these can only be considered as illustrations of the system sensitivity for the tested strategies at different scales, it is the hope of the authors that such examples contribute to a more balanced view on prioritization among the wide range of identified efficiency increasing measures.

## 2. Unit process level

Discrete part manufacturing processes are defined as production processes in which the output can be identified and is measurable in distinct units rather than by weight or volume as in process industry. In literature, different taxonomies are available to order the wide variety of discrete part manufacturing processes [46,198]. Fig. 1 shows the typical system boundaries of a unit process.

In the content of this paper, the boundaries of a unit process typically coincide with individual machine tools as the smallest unit of which production systems are composed. In this approach, hybrid workstations, combining multiple processes on a single machine structure, can be considered as the sum of multiple individual unit processes that can be analyzed separately.

While some preliminary environmental studies for machine tools in material removal processes (e.g. turning and milling) indicate that more than 90% of the environmental impact is due to the consumption of electrical energy during the use stage [23], other authors reporting detailed analysis observe significantly larger contributions of the machine tool construction [9,42, 172,229]. With a minimum of approximately 83% and 60% of the total impact for cutting machine tools and press brakes respectively, the use stage however systematically proves to be the dominant contributor to the total life cycle environmental impact of machine tools. Therefore, Section 2 of this paper focuses on the energy and resource consumption during the machine tool use stage. While the impact assessment of the use stage is covered in Sections 2.1–2.3, the potential for environmental improvement is treated in Section 2.4.

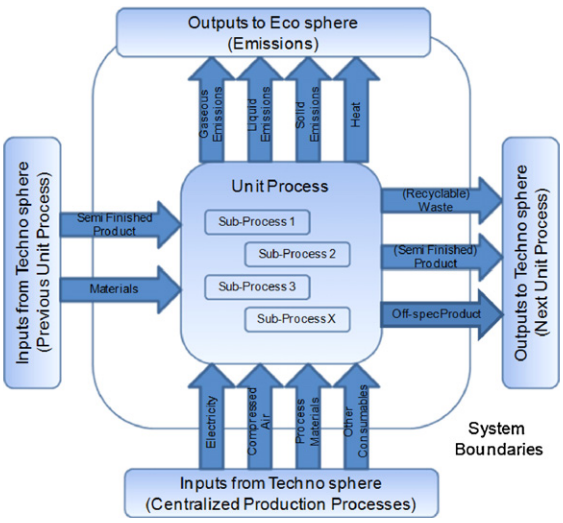


**Fig. 1.** System boundaries of a unit process [111].

### 2.1. State of affairs in unit process data availability

#### 2.1.1. Coverage of unit process impact by existing LCI databases

The Ecoinvent database, as supplied by the Ecoinvent Centre [61], is one of the most widely consulted sources of consistently and transparently documented life cycle inventory (LCI) data. In this database, in contrast to materials production, manufacturing processes, as used for discrete part manufacturing, are less well documented in terms of the overall environmental impact. On the one hand, the coverage of the wide range of available manufacturing processes is limited to more conventional processes, such as turning, milling and casting, while commonly used processes, such as, for example, electrical discharge machining and additive manufacturing processes, are lacking in the database. On the other hand, most of the available data on manufacturing processes are incomplete: the focus is often limited to theoretical energy consumption, and data on emissions are rarely found [185]. For other LCI databases, such as the U.S. Life-Cycle Inventory Database [146], similar observations can be made.

It is to be noted that various industrial sectors provide LCI-data about their products. Organizations like the International Iron and Steel Institute [64], the European Aluminium Association [56] and Plastics Europe [54] provide extensive LCI data for respectively steel, aluminum and plastic half products, while the BUWAL database covers a wide range of packaging materials [22]. Despite the very useful work of the respective sector organizations, the scope of these LCI databases is typically limited to primary material production (e.g. sheets, foils, and profiles) and recycling processes. A comprehensive overview of the state of the art in environmental impact assessment of unit processes is provided by Duflou et al. [53].

#### 2.1.2. Sectorial interest in the environmental performance of machine tools

Research contributions by different machine tool builders demonstrate the increasing interest in the environmental (mainly energetic) performance of the equipment they develop, [40, 136,213]. CECIMO, the European Machine Tool Builder Association, launched a self-regulatory initiative for supporting the identification of measures to improve the energy and resource efficiency of the machine tools of their members [23]. The ongoing ISO standardization efforts 'Environmental evaluation of machine tools' (ISO 14955) and 'Automation systems and integration – Environmental and energy efficiency evaluation method for manufacturing systems' (ISO 20140) as well as the Life Cycle Initiative of UNEP–SETAC [194] are likely to reinforce the trend towards more environmentally conscious manufacturing.

### 2.2. Methodologies for the determination of unit process energy and resource consumption

The basic procedure for a life cycle inventory (LCI) effort of a manufacturing unit process is similar for a wide range of manufacturing processes and can in principle cover a full process taxonomy like DIN8580 [46,63], including auxiliary support processes such as compressed air supply, centralized cooling and transport systems. The consumption of energy and resources as well as the generated waste and process emissions should be determined and allocated to the individual production process. In this section, energy demand is interpreted as net extraction from the power supply system. Conservation of energy and possible reuse in other unit processes is not taken into consideration here, but will be considered as part of the energy and exergy analysis covered in Section 3. Collection and documentation of LCI data can be obtained in different ways, starting from theoretic calculations until detailed process measurements and analysis.

*2.2.1. Equations to calculate the (minimum) theoretic process energy and resource consumption*

Abele et al. [1] describe a method for life cycle inventory analysis of production processes using theoretic equations to calculate the energy and resource consumption as well as waste and process emissions. Equation 1 shows the general formula for the total energy demand during production.

$$E_{total} = E_{th} + E_{additional} + E_{periphery} \quad (1)$$

where, $E_{th}$ is the active energy theoretically needed to obtain the physical process effect, and represents the minimum energy demand of the production process. $E_{additional}$ and $E_{periphery}$ stand for the additional energy demands of the machine tool (e.g. energy to cover efficiency losses, or energy for machine functions such as central control) and peripherals (e.g. cutting fluid pump) respectively. Abele et al. [1] provide specific equations for a wide variety of production processes.

Overcash et al. [150] developed a generic methodology to gather unit process life cycle inventories (UPLCI) using rules of engineering and industrial practice to calculate energy and mass losses. As described below, this approach is also used as screening approach within the $CO_2$PE! – Initiative.

*2.2.2. Detailed process measurements and analysis*

Within the framework of the $CO_2$PE! – collaborative research programme [30], a life cycle assessment (LCA) oriented methodology for systematic inventory analysis of manufacturing unit processes (referred to as unit process life cycle inventories, UPLCI) has been developed which comprises two approaches with different levels of detail [111].

The *screening approach* relies on representative, publicly available data and theoretical 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 this approach 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 [150]. These data serve to guide the more detailed and complete in-depth approach leading to more accurate LCI-data as well as the identification of the potential for energy and resource efficiency improvements of the involved manufacturing unit process. As far as the energy consumption quantification effort is concerned, the methodology under development as part of the ISO TC39WG12 efforts [98] corresponds well with the $CO_2$PE! in-depth approach. Fig. 2 shows the framework of this $CO_2$PE! – UPLCI – methodology as explained more in detail in the next paragraphs.

*2.2.2.1. Goal and scope definition.* First, the goal and scope of the study should be clearly defined and must be consistent with the intended unit process. The most important parts of the scope definition to be considered are the system boundaries and the functional unit of the intended process. Furthermore, the machine tool architecture and process parameters are investigated and all subsystems that are considered relevant for design optimization are identified and located within the machine tool.

As illustrated in Fig. 1, the system boundaries are set to include only the operating stage of a single, isolated manufacturing unit process, disregarding materials processing, production, transport, maintenance and disposal of the machine tool itself. For processes using consumables (e.g. compressed air, lubricants, and process gases) delivered by central systems, the related impacts are taken

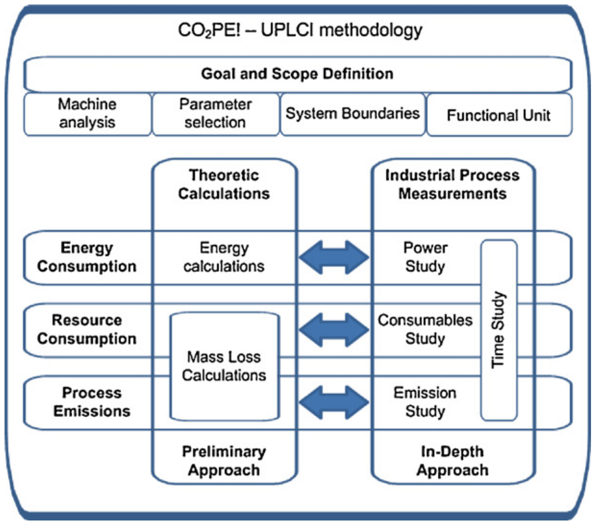


**Fig. 2.** $CO_2$PE! – UPLCI – Methodology [111].

into account based on the available average data per unit of consumable as documented in existing LCI-databases such as EcoInvent for a range of auxiliary unit processes.

Besides a process dependent functional unit, a generally applicable reference flow of 1 s of processing time for a specified load level of a unit manufacturing process for a given material, based on a working scheme of 2000 h/year including some specified use modes is used.

*2.2.2.2. Process inventorisation.* The in-depth approach of the process inventorisation is based on industrial measurements and includes a time, power, consumables as well as emission study. First, a statistical time study is performed in order to identify the different use modes of a machine tool and their respective share in the covered time span. The energy consumption of the machine tool is obtained by measuring the total machine tool power consumption over a specified time period. By measuring individual power consumption patterns for all relevant active energy consuming subunits in each production mode, the energy and corresponding environmental impact optimization potential can be identified as output towards machine tool designers.

Of course, the usefulness of such data collection efforts largely depends on the completeness and quality of the data capturing and measurements. While Herrmann et al. [84] provide an overview of energy consumption metering procedures and tools, Kara et al. [105] present an overview of the evolution and the latest developments in power measurement and monitoring systems. An exemplary list of metering devices is given to demonstrate how features of the different measurement instruments can be matched for certain measurement tasks in different application levels. For automated energy monitoring of machine tools, Vijayaraghavan and Dornfeld [212] introduce a framework based on event stream processing to automate the monitoring and analysis of energy consumption in manufacturing processes.

Parallel to the time and power measurements, the resource consumption (e.g. compressed air, lubricants, process gasses) are measured for each process material in each production mode. While the raw material flow does not represent manufacturing induced impact, the amount of waste created is process dependent and is therefore included as consumable. Finally, also an emission study takes place when relevant (e.g. mass balance abnormalities, use of hazardous materials). This study includes gaseous, liquid and solid emissions as well as heat losses.

Herrmann et al. [88] proposed a framework to visualize the environmental impact of manufacturing processes using virtual reality.

### 2.3. Data collection efforts: case studies

Various energy and resource consumption data collection efforts are described in literature using one of the above mentioned approaches. An overview of available case studies using the $CO_2$PE! – Screening approach can be found on the UPLCI-website [202]. This section provides a selection of case studies organized according to the DIN 8580 taxonomy [46,63], which distinguishes six main categories of discrete part manufacturing processes: Primary shaping, Forming, Separating, Joining, Coating/Finishing and Processes which change the material properties. For each of the first three categories some case study results, based on industrial measurements, are presented in the next paragraphs.

#### 2.3.1. Primary shaping processes

Mognol et al. [133] investigated the energy consumption of three rapid prototyping systems: Thermojet (3DS), FDM3000 (Stratasys) and EOSINT M250 Xtended (EOS). Since the electrical power consumption of these systems was found to be approximately constant over different operating modes, the authors concluded that the manufacturing time is the determining factor for the total energy consumption.

More detailed studies, covering all aspects of impact generating energy and material flows, allow to provide a more refined analysis. A case study about the environmental impact of Selective Laser Melting (SLM) and Selective Laser Sintering (SLS) processes has been conducted at the KU Leuven [110]. In-depth time studies were performed on three different EOSINT P760 SLS machine tools. The non-productive modes comprise machine tool cleaning, preheating and cooling down. The productive modes are responsible for approximately 87% of the total production time, and can be subdivided further into three main modes: the laser exposure mode, the recoating mode and observed other activities like filling the feed containers. Based on 63 batches (5801 products), Fig. 3 presents the time distribution for products made of PA2200 with a layer thickness of 120 μm.

Fig. 4 shows the different power levels during the productive mode of an EOSINT P760 machine tool. Besides the laser cooler, the process heating units are the largest energy consumers.

Besides energy, SLS processes also need a process gas (typically $N_2$) to create an inert working atmosphere. Since this atmosphere is created by an internal, compressed air driven $N_2$-generator, the compressed air consumption of 20 $m^3$/h should be taken into account. Furthermore, based on industrial observations, only half of the residual powder is recyclable, which represents a waste material rate of approximately 45% of the input powder.

For a sample batch with a total product volume of 3.3 kg and production time of 15 h, the major contributor to the total environmental impact was found to be the waste of raw material (see Table 1). Major opportunities to reduce the environmental impact of the SLS process for polymers seem to be to identify measures that result in a higher material utilization efficiency and/or methods to regenerate the residual powders for reuse.

The majority of discrete part casting operations occurs through sand casting (60%) [203]. The sand casting process involves pouring of molten metal into a mold composed primarily of sand and binders. The binders used are primarily chemical (thermal setting or catalytic reactions) and clay (green sand casting), with green sand molds used in about 90% of part production [205]. To form internal voids in the parts, chemically-bound cores are used, which are stronger than green sand. Unlike permanent mold casting, sand molds are destroyed after each use, with the majority of the sand usually recycled into new molds and cores. The environmental concerns of sand casting include virgin material consumption, solid wastes, and hazardous air emissions, which have been addressed over the past several decades. Sand casting utilizes large amounts of sand; many foundries in the U.S. extract sand from the sand dunes of the Great Lakes [220]. While sand can be reused, it breaks down over time. In the U.S. about ten million tons of waste foundry sand are generated annually [206]. In addition, the various types of green sand and chemical binding systems form a variety of air emissions, which can be harmful to workers [12,33,138]. Dalquist and Gutowski [37,38] investigated sand casting and die casting using life cycle assessment. Haapala et al. [71,72] have established a model to compare the environmental performance of sand casting process design alternatives.

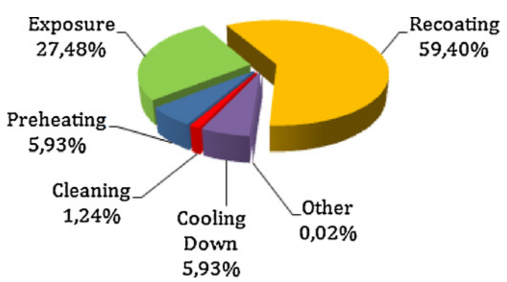


**Fig. 3.** Time distribution for SLS production modes (PA2200, layer thickness of 120 μm) [110].

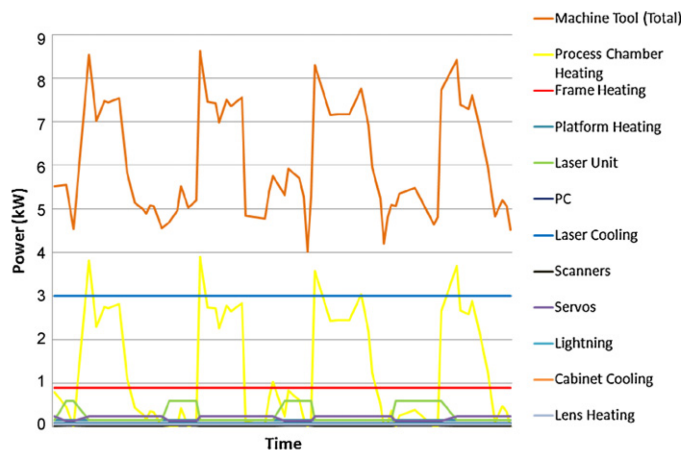


**Fig. 4.** Power levels during the productive modes of an EOSINT P700 Selective Laser Sintering machine tool [110].

In these case studies the contribution manufacturing operations can make to impact avoidance has not been taken into account when compared to more conventional manufacturing processes.

For additive processes an example of such an effect is illustrated by Morrow et al. [137]. The authors present three case studies to reveal the extent to which Direct Metal Deposition (DMD) manufacturing of molds and dies can achieve reduced environmental emissions and energy consumption relative to conventional manufacturing procedures. It is shown that DMD's greatest opportunity to reduce the environmental impact of tool and die manufacturing comes from its ability to enable laser-based remanufacturing.

For injection molding processes, Thiriez and Gutowski [197] obtained specific energy consumption values of 3.39, 1.67 and 1.46 MJ/kg for hydraulic, hybrid and all-electric machine tool variants, respectively. For hydraulic and hybrid machine tools, the specific energy demand decreases with increasing throughput.

#### 2.3.2. Forming processes

Several authors investigated the energy consumption of air bending [39,52,108,172] and observed that the standby energy is substantial. On the one hand, due to diverse operator activities, the

**Table 1**
Environmental parameters of sample batch for SLS processing [110].

| | | Impact (mPts) | % |
|---|---|---|---|
| Energy | 120 kWh | 3120 | 31.9 |
| Compressed air | 340 $m^3$ | 1598 | 16.3 |
| Waste material | 10.3 kg | 5068 | 51.8 |

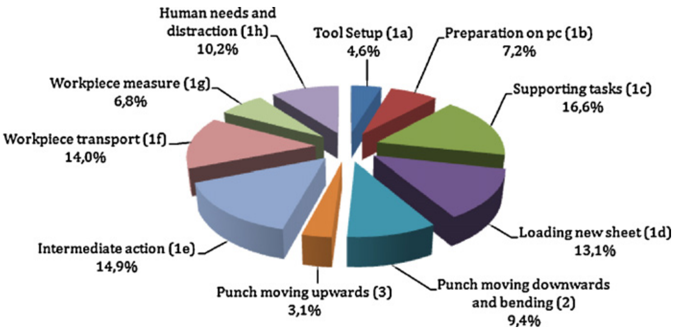


**Fig. 5.** Time distribution for the production modes of the air bending process [52].

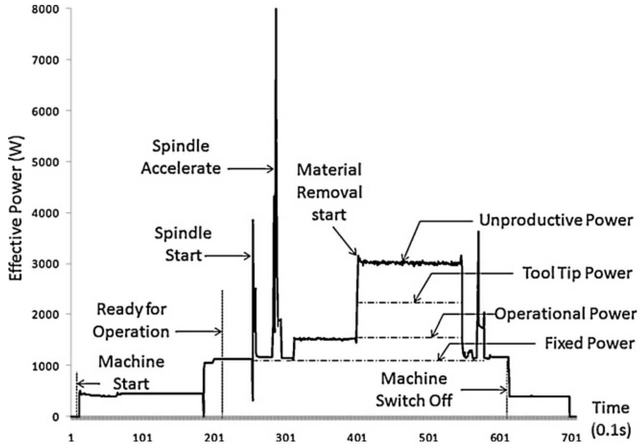


**Fig. 6.** Power profile of a turning process [121].

time share of the standby mode (mode 1) is very high as indicated in Fig. 5. On the other hand, the power levels during the standby mode are significant, ranging from 1.4 kW to 5 kW for conventional hydraulic press brakes with a maximum capacity between 80 and 170 ton. Similar conclusions were drawn by Shi et al. [179] for stamping processes.

Ingarao et al. [95] outlined the state of the art from a resource efficiency point of view for sheet metal forming technologies, covering the total life cycle starting from raw materials production up to recycling technologies.

*2.3.3. Separating processes*

Dahmus and Gutowski [36] showed that the cutting energy consumed by a modern automatic machine tool during machining is less than 15% of the total energy demand. Fig. 6 illustrates a typical power profile of a turning process [121], which divides the total machine tool power in four power levels:

- *Fixed power*: power demand of all activated machine components ensuring the operational readiness of the machine.
- *Operational power*: power demand to distinctively operate components enabling the cutting as performed in air-cuts.
- *Tool tip power*: power demand at tool tip to remove the workpiece material.
- *Unproductive power*: power converted to heat mainly due to friction during the material removal.

As shown in Fig. 7, an average breakdown of the fixed energy consumption of machining processes is given by Li et al. [121].

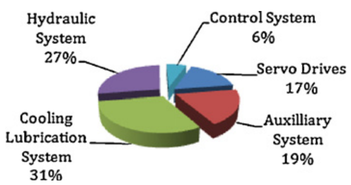


**Fig. 7.** Average fixed energy breakdown adapted from [121].

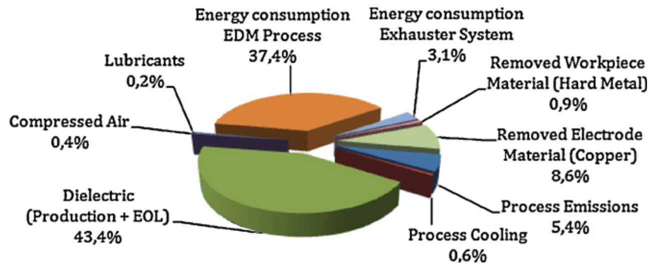


**Fig. 8.** Distribution of the environmental impact during 1 h of EDM roughing [109].

An empirical model to characterize the relationship between energy consumption and process variables for chip forming material removal processes was presented by Kara and Li [106] and Diaz et al. [43]. Eq. (2) shows the developed model predicting the energy consumption of turning and milling processes with deviations of less than 10% on the measured values, which indicates that one generic model could be adopted to describe the specific energy consumption under various cutting conditions.

$$SEC = \frac{C_0 + C_1}{MRR} \quad (2)$$

where, *SEC* is the specific energy consumption [kJ/cm$^3$], *MRR* is the material removal rate [cm$^3$/s] and $C_0$, $C_1$ are machine tool specific coefficients.

The environmental impact of $CO_2$ laser cutting was analyzed by Duflou et al. [51] and Oliveira et al. [149]. In addition to energy, the assist gases consumed in the process (e.g. nitrogen and oxygen) and waste generated were also found to significantly contribute to the total environmental impact of the use stage of a laser cutting machine tool. The laser source and chiller are responsible for more than 80% of the total consumed energy.

Dhanik et al. [40] as well as Kellens et al. [109] investigated the environmental impact of the use stage of Electrical Discharge Machining (EDM) processes. Of all subunits, the different dielectric pumps proved to be the dominant energy consumers.

Fig. 8 summarizes the distribution of a range of different impact creating factors for 1 h of EDM roughing with a copper electrode, on a hard metal workpiece. The environmental impact is mainly caused by the consumed electrical energy (40.5%) and the dielectric fluid (43.4%).

*2.4. Energy demand and resource consumption reducing strategies*

Different strategies can be considered while aiming for the reduction of environmental impact at a unit process level. Machine tool manufacturers can work on the process efficiency by optimizing the machine tool design, while process planners can work on process parameters optimization, on machine tool selection or can consider process substitution.

*2.4.1. Effects of optimized machine tool design*

*2.4.1.1. More efficient machine tool components.* An obvious way to improve the environmental performance of machine tools is the development and adapting of more energy efficient components. Among many others, the Self-regulatory Initiative (SRI) of CECIMO [23] as well as the ISO standardization effort on the environmental evaluation of machine tools [98], list potential measures towards more energy and resource efficient machine tool components. Examples can be found in more efficient drives, pumps, and spindles. Another example can be found in switching from active to passive workpiece clamping, offering significant reductions of the time span in which active power is required for a wide range of processes [98].

Abele et al. [2] explored the potential of an energy optimized spindle unit with an adapted electric drive train. An axiomatic approach to identify structural improvement potential with guidance for the optimal implementation sequence of measures was proposed by Zein et al. [226].

*2.4.1.2. Technological changes.* Instead of the gradual improvement of current machine tool technologies and devices, a shift to alternative, innovative technologies can yield significant environmental gains. For example, adopting new laser source technologies, such as new generations of fiber and diode lasers, to replace conventional $CO_2$-lasers, holds the promise of an increase from around 12% for $CO_2$-lasers to approximately 30% in laser source efficiency, while simultaneously resulting in lower output power requirement levels for most materials due to more favorable absorption in the near infrared wavelength range for most commonly processed materials [52].

*2.4.1.3. Waste recovery within a machine tool.* Another way to improve the energy and resource efficiency of manufacturing processes is the recovery of waste streams and heat losses within a machine tool. A recent patent [213] describes a system for recovering heat losses of a laser cooler system using a Sterling engine that drives a compressed air generator. A filter system separates nitrogen and/or oxygen from the compressed air that can be used as assist gas within the machine tool itself.

Another example related to material resource efficiency can be found in the commonly applied recycling and remelting of runners by casting processes.

A practical method to separate and collect un-sintered powder materials for polymer laser sintering processes has been developed by Dotchev and Yussof [49]. In order to control the input material quality and use the fresh powder more efficiently, the authors suggest using different grades according to the melt flow rate of the recycled powder.

In terms of energy recovery the kinetic energy recovery system (KERS) is a possible method of improving energy efficiency. Investigations by Diaz et al. [41] show reductions of the average energy consumption of high-speed cutting processes up to 25% depending on workpiece geometry and machining time.

*2.4.1.4. Integrated or central peripherals.* Consumables such as compressed air and process gases can be produced within the machine tool itself or delivered from central support systems, causing different environmental impacts depending on the chosen solution. The same consideration applies for local or centralized supply of cooling and lubrication facilities. A comprehensive literature review about compressed air energy use, savings and payback period of energy efficient strategies was compiled by Saidur et al. [170]. An overview of different derived energy saving opportunities at the machine level is shown in Fig. 9. A comprehensive overview of compressed air systems design considerations is provided in Section 4.3.

### 2.4.2. Effects of optimized process control

*2.4.2.1. Selective actuation of non-continuously required devices.* An easy and highly effective way to reduce the electrical energy consumption can be found in selectively shutting down devices of which the functionality is not required in specific operational modes (e.g. switching to a less energy consuming stand-by level). Switching from conventional, continuously active hydraulic systems for air bending towards servomotor driven pumps with direct control of hydraulic pistons, allows the required standby energy to be reduced significantly (up to 65%) as the servomotors only need to be activated during the actual bending operation [39,108,172].

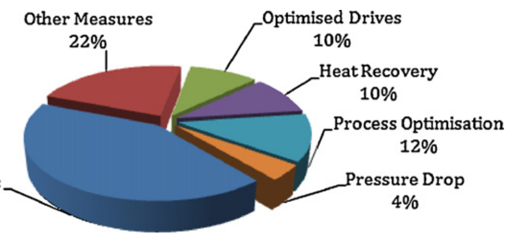


**Fig. 9.** Relative importance of different energy saving measures for compressed air systems.
Adapted from [170].

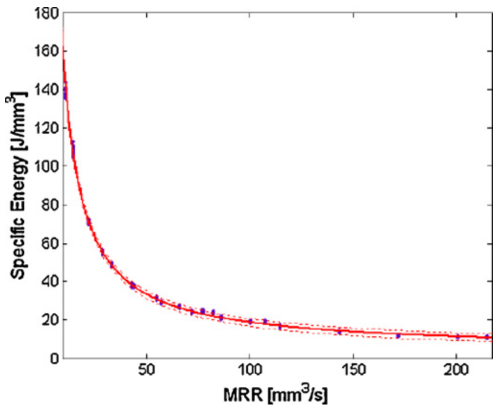


**Fig. 10.** Specific energy demand for milling processes as function of the material removal rate (MRR) [43].

*2.4.2.2. Reducing idle production times.* Besides the required power level of machine tools, the second parameter in energy demand is time. Therefore reducing the unproductive idle time during a manufacturing operation contributes to an increase in overall energy efficiency. Using functional states for common suppliers, Schmitt et al. [176] proposed a self-optimization model to control the energy consumption depending on the usage profile of a machine tool, automatically switching to the most optimal production mode.

*2.4.2.3. Optimized process parameters.* The selection of process parameters can have a significant influence on the consumed energy and resources. Diaz et al. [41,43] as well as Mori et al. [136] illustrated that the energy consumption for drilling and face/end milling can be reduced by setting the cutting conditions (cutting speed, feed rate and cutting depth) high, thereby shortening the machining time, yet within a value range which does not compromise tool life and surface finish. Fig. 10 shows the specific energy demand for milling processes as function of the material removal rate (MRR).

For deep hole machining, the power consumption can be reduced with an adaptive pecking cycle, which executes pecking as needed by sensing cutting load. Finally, synchronization of the spindle acceleration/deceleration with the feed system during a rapid traverse stage can reduce the energy consumption up to 10%. Similar results were presented for drilling processes by Neugebauer et al. [140].

Furthermore, Neugebauer et al. [142] defined preferential working spaces with limited power consumption for robot based assembly systems.

*2.4.2.4. Energy and resource efficient process modeling and planning.* Various models for energy and resource efficient process modeling, planning and scheduling have been presented in literature. Sheng et al. [178] were among the first to also include environmental factors in their multi-objective process planning models in addition to traditional criteria such as production rate, quality and costs. Over the last decade, several variants of models have been proposed, all defining the most energy efficient or ecological process or process chain, using the available data of different manufacturing unit processes and auxiliary equipment (e.g. robots and compressed air systems). Among many others, examples at unit process as well as system level can be found in [8,44,57,86,141,144,218].

### 2.4.3. Effects of process/machine tool selection

*2.4.3.1. Process selection.* Energy and resource efficiency comparison and deduced selection of alternative manufacturing processes could help to reduce the total environmental product impact. For example, Pecas et al. [152] developed a model to compare the life cycle performance of mold manufacturing techniques suitable for low production volumes. The model includes three independent but essential and complementary performance criteria: economic, technical, and environmental. Two candidate technologies were evaluated: one involving a mold made of a spray metal shell backfilled with resin and aluminum powder and another based on the machining of aluminum. While the former mold offers the best solution in terms of economic and environmental aspects, the latter has a better technical performance.

Pusavec et al. [156,157] present cryogenic and high pressure jet assisted machining (HPJAM), using liquid nitrogen as a coolant, as viable machining technologies offering a cost-effective route to improve economic and environmental performance in comparison to flood cooling in conventional machining.

Brockhoff and Brinksmeier [20] as well as Reinhardt et al. [166] proposed grind-hardening as a resource efficient alternative to the traditional hardening processes using induction.

Klocke et al. [112] concluded that the directed supply of lubricoolant, with supply pressure as the dominant process parameter; could lead to significant reduction of tool temperature up to 30% compared to conventional flood cooling.

*2.4.3.2. Optimal machine tool capacity.* For most manufacturing processes the fixed power level, which corresponds to a non-loaded machine tool in stand-by mode, has a significant contribution to the total power consumption. Therefore, a proper selection of the right equipment (and related maximum capacity) could reduce the energy consumption. An example can be found in Fig. 11 which shows potential energy savings up to 50% by optimizing the selection of a laser cutting machine tool [52]. Target here should be to use machine tools as near as possible to their maximum capacity.

*2.4.3.3. Optimal resource consumption.* In addition to energy consumption, the consumption of resources, such as lubricants, compressed air, and process gasses also causes environmental impact. In the domain of lubricants, several researchers investigated strategies such as *Dry Machining* and *Minimum Quantity Lubrication*, aiming to avoid or limit resource consumption (e.g. [7,216]).

In parallel, environmentally benign fluids have been developed for operations which still require lubricants (e.g. [5,81,85, 119,148,221]). A comprehensive overview of important developments of new, environmentally benign lubricants for metal forming processes was published by Bay et al. [13].

Clarens et al. [27] provided a quantitative assessment of emissions and energy consumption as well as a semi quantitative assessment of health impacts associated with environmentally

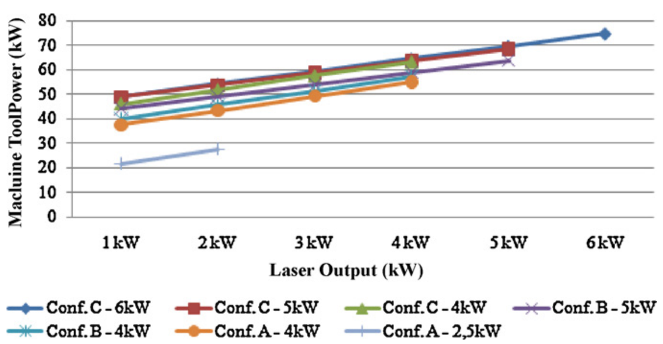


**Fig. 11.** Power consumption in cutting mode in function of the laser output level for 7 different laser cutting machines (3 configurations combined with different $CO_2$ laser sources with indication of the maximum achievable output level) [52].

adapted metalworking fluid systems. A comparative life cycle assessment of water and gas-based systems shows that delivery of lubricants in air rather than water can reduce solid waste by 60%, water use by 90% and aquatic toxicity by 80%, while virtually eliminating occupational health concerns.

## 3. Multi-machine level

A production system is a combination of different production processes and typically is composed of diverse machines for processing or transportation as well as personnel. All these production factors are being planned and controlled by a production management system. All involved technical equipment, with certain energy and media consumption profiles, result in cumulative load curves for such measures as power or compressed air for the whole process chain or the plant respectively.

### 3.1. Multi-machine 'ecosystems'

A multi-machine 'ecosystem' describes a network of machines within a factory. The connection of these machines can be in a parallel organization, like in a job shop production, or in a sequence organization, like a process chain. Due to the structure of the network, the output of one process may be the input for another. The qualitative condition of the output is not relevant. Thus, by-products, scrap, energetic emissions (waste heat, waste air, mechanical energy, etc.) or waste material, which arise in the production of products in one process, are inputs on the multi-machine level (Fig. 12). In this context the energetic or physical flows can be classically recycled within the process chain, but also be reused in another process chain nearby. At the end of these multiple use stages, the further non-useable energetic or physical output leaves the system boundary.

In the following, methods and tools are presented to capture and track energy and material flows in a multi-machine ecosystem. Furthermore, examples are presented of implementation possibilities in such ecosystems.

*3.1.1. Energy flow and machine ecosystems*

The multi-machine ecosystem can be described as an energy cascade system with the purpose of completely utilizing energy flows (Fig. 13) [67,77,182]. A cascade example is the thermal down-flow of heat. The thermal energy flows from a higher temperature level to the ambient temperature. During this downfall, the heat can be utilized in multiple processes [4]. Thereby the quality of the energy flow decreases gradually with increasing duration of utilization.

*3.1.1.1. Modeling methodologies of energy flows in an ecosystem.* The foundation for description, acquisition and analysis of all energetic flows into and out of a multi-machine ecosystem are the energy,

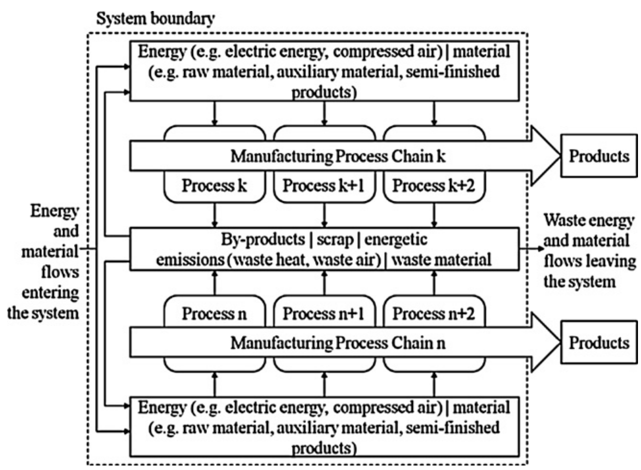


**Fig. 12.** Multi-machine ecosystem.

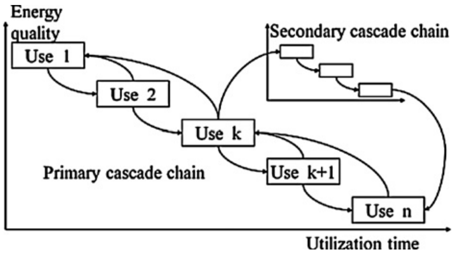


**Fig. 13.** Energy cascade system [182].

exergy and entropy concepts. These three concepts are defined by the first and second law of thermodynamics. The first law describes that energy cannot be destroyed or created, it is conserved, and it can just change form. The energy only serves as a carrier of quality, and it is the quality that is consumed during the conversion of energy [214]. The second law describes that energy has quality and quantity. Quality and quantity of energy or 'work potential' can be described by the properties exergy and entropy [10,15,78,214].

The energy flows into and out of a system along paths of mass flow, heat transfer and work [15]. The exergy is that part of energy that is convertible into all other forms of energy; it represents the 'useful' energy respectively the technical working capacity of the streams that flow to the system [15,214]. In contrast to energy, exergy can be destroyed. The amount of destroyed exergy is proportional to the generated entropy. In order to analyze a machine, an energy analysis, based on an energy balance according to the first law, can be carried out. The disadvantage is that in discrete manufacturing, the energy analysis often only measures one resource: electrical energy and other process connected resources are not taken into consideration. Furthermore, no information on the system energy degradation is available. To overcome these disadvantages, an exergy based method can be used to analyze a technical system.

The exergy method allows the complete measure of in- and outgoing system streams and the derivation of information about energy inflation in the system [15,78]. Thus, a minimization of all exergy losses leads to a minimum energy consumption of the process [162]. Furthermore, it can be derived that the exergy is the property that has an economic value [134]. The concept allows the identification of energetic discharges. Beside the reduction of these energetic discharges, the concept can identify potentials for energy based machine ecosystems.

The exergy analysis allows the rational comparison of different energy forms and different process structures to identify optimal process parameters. In order to fulfill this task, the exergy analysis calculates exergy losses on the basis of entropy functions of all process streams. The height of the exergy losses depends on the difference of the current system state to the state of the environment, the so-called 'dead state'. In the dead state a thermodynamic equilibrium of the considered system with its environment exists. Furthermore, there is no possibility of a spontaneous change within the system or the environment, nor can there be an interaction between them resulting in work [134]. When using the exergy analysis to improve process structures, the components of the process system have to be analyzed and the whole system has to be compared with various different process alternatives [162]. Thus, the exergy analysis allows to determine the location, type and magnitude of the dissipation of energy [3,15,21,191].

The advantage of the exergy analysis is that it can help to locate energetic discharges in a system, which either are not identified or misevaluated by the energy analysis. Moreover, these discharges can be analyzed by calculating the exergy destruction rates under changed process parameters and afterwards comparing it with rates of the original process [134].

Renaldi et al. [167] presents a comparison of different exergy efficiency definitions for the comparison of three different manufacturing processes on the basis of an exergy analysis. The considered manufacturing processes are laser cutting as a subtractive process, the Selective Laser Sintering as an additive process and bending as mass-conserving process. For each process, the input and output variables are determined and subsequently form the basis for the exergy analysis. The conclusion of the examination is that system analyses on the basis of exergy efficiencies are able to appropriately present the resource efficiency of the involved manufacturing processes.

*3.1.1.2. Example of energy flows in a multi-machine ecosystem.* In the following, examples are presented where the exergy concept is used to analyze and describe a technical system.

Creyts et al. [34] use the exergy analysis of a metal machining process to understand and to present the energy flows in a multi-machine ecosystem. The used model consists of a process model to determine the waste stream characteristics and an exergy model that performs the extended exergy analysis on the resulting waste streams. The examined process is the machining of an aluminum workpiece with a water–oil emulsion. In addition to the actual machining process, particularly the treatment and disposal of waste streams (such as metal working fluid, cutting swarf, etc.) were exergetically examined. After the modeling and calculation of the existing process, the influence of the input parameters on the exergy was examined by a sensitivity analysis. Besides the analyses of the influence of changed process parameters, Creyts et al. [34] perform an exergetical comparison of the used technologies for the treatment and disposal of waste streams with alternative process configurations and technologies. Both examinations showed that the exergy analysis is a suitable tool to integrate environmental criteria into the planning stages of industrial process system design. Further examples are given, amongst others, by Szargut et al. [191,192], Brodyansky et al. [21], Kotas [114], Meyer [131], Dinçer et al. [47], Gutowski et al. [69] and Saiganesh et al. [171].

While an energy analysis can be used to quantify the efficiency of standalone machine tools (Section 2), opportunities for improvement at the level of energy reuse are often requiring a systems approach involving multiple unit processes. In most cases, the industrial waste heat is considered as source for energy flow cascades. An example of cascading energy utilization is the use of industrial waste heat of a melting furnace as an input flow for a heat treatment process. This is the case for example for the use of hot flue gases of one process to preheat metal bolts, which have to be processed, in a different process. Therefore, the flue gases flow in the counter direction of the material flow. Thus the energy contained in the flue gas is reused [14,154]. Another option is the heat recovery of hot off gases in steel foundries. Due to constructive measure at the furnaces, a twin shell system can be built for heat recovery. In this system, iron melts in one half of the furnace while the other half is being loaded. The hot off gases from the melting side are piped to the other side to pre-heat the charge. Precondition in this context is that the temperature level of waste heat is higher than the required process temperature of the heat utilization. Furthermore, there should be a temporal concurrence between heat supply and demand and the heat source and sink should be located at close distance [14]. Beside the multi-machine utilization of industrial waste heat, there is a possibility to supply the corporate internal heating network via a heat exchanger with thermal energy in cases where ambient temperature requires conditioning of the work environment.

Another example of a multi-machine ecosystem is the generation of electricity from industrial waste heat by using a Rankine cycle (RC) [6,186]. The Rankine cycle is a thermodynamic cycle with the greatest efficiency for the conversion of low temperature heat into electricity. A modified version is the organic rankine cycle (ORC). In this case an organic fluid is used instead of water as the working fluid. Especially for low temperature applications the ORC has more benefits than the RC due to better specific properties of the organic fluids. Larjola [117] demonstrated that the ORC-process can use the exhaust air of a process (e.g. gas turbine, blast furnace, etc.) as input. The output of an ORC-process is electric power, produced from the given heat source. In order to determine the electrical output of the ORC-process, the exergy analysis can be used to calculate the cycle process.

The utilization of a thermoelectric generator (TEG) can be considered as another possibility in recovering industrial waste heat [16]. The TEG is based on solid-state thermoelectric materials which are able to directly convert heat into electricity due to the Seebeck effect. It is a potentially preferable approach especially if there are difficulties in effectively transporting the waste heat from the source to a separate energy conversion system [58]. The efficiency of TEG devices can be expressed by means of the dimensionless figure of merit ZT. At present, the implementation of TEG is still limited in appliances where the durability and maintenance-free operation are among the most important criteria [16]. Applications in more abundant products, such as vehicle exhaust systems, are foreseeable in the near future along with an increase in TEG performance. A study by the U.S. Department of Energy concluded that applications in aluminum smelting, glass manufacture and cement production can be practical at a ZT value of two [80]. As an illustration, in one of the latest research outputs in TEG, researchers managed to achieve a ZT value of 1.8 at 850 K [155].

Another case of recovering energy is usage of industrial waste heat for preheating necessary media in other processes. As example, [196] assesses the effect of reusing heat that is occurring in the context of large scale compressed air generation for a weaving mill. It is used to preheat steam, which is needed for the sizing process just before the weaving, resulting in significant energy savings of over 20%.

#### 3.1.2. Material flow and machine ecosystems

Similar to the energy flows, the material flows in a multi-machine ecosystem can be utilized to increase material efficiency. The material based output of one process is the input for another.

A possibility to describe the material flows in a multi-machine environment is the use of the input–output analysis. This concept provides the foundation to identify potentials of material based machine ecosystems and is described in more detail in Section 6.2. With regard to the identification of input–output flows on the unit process level, a description and detection tool is the material/energy input–output analysis concept. In this analysis the monetary units are substituted by material and/or energy units [11,118]. The concept is commonly used to analyze the flows between different industrial sectors of an economy. In this context the method records material and/or energy flows among the units within the company or the supply chain [31,73,145,187]. Thus, this concept offers a starting position for the material flow-based analysis of a multi-machine ecosystem.

*3.1.2.1. Example of resource flows in a multi-machine ecosystem.* In the following, two examples of a material flow-based multi-machine ecosystem are presented. Further examples are given, among other, by Munoz and Sheng [139], Konijn et al. [113], Sutherland and Gunter [189] and Xue et al. [223].

Logožar et al. [126] present a first step into the direction of a multi-machine ecosystem in the aluminum production process. As part of the melting process and the following processing steps to produce aluminum tubes, rods and bars, aluminum scrap is generated. To increase the resource and energy efficiency the scrap was collected within the different units and reinstated as an input flow in the melting process. The advantage of this approach is that the remelting of recycled aluminum requires only about 5–10% of the energy used for primary production [160].

Another example of even more direct reuse of waste flows is presented by Tekkaya et al. [66,151,193]. The authors investigated the reuse of aluminum AA-6060 milling and turning chips in direct hot extrusion. This research has shown that using billets made of AA-6060 chips can lead to similar mechanical and microstructural properties as use of conventional cast aluminum billets. Investigation of material removal by cutting or drilling from the extruded profiles has even demonstrated improved properties due to a reduced chip length.

Gomes et al. [65] investigated the use of compartmentalized metalworking fluids for treatment and cleaning of foundry sand. In this case, fluid emulsion (water and mineral oil) that was ready to be disposed was instead divided through a separation process into the respective components of water and mineral oil. The treated water was used within the company as a substitute for tap water. The treated water has, compared to the tap water, higher values in terms of hardness, alkalinity, nitrates, etc., but was however still suitable for use as cleaning fluid of foundry sand. But Gomes et al. [65] also point out that the implementation of this cascade utilization is limited. On the one hand due to limited availability of treated water, and on the other hand due to the limited economic and environmental potential in consequence of the high intensity of energy and resource consumption during the treatment process.

### 3.2. Process chain design and control

The load profiles of single machines add up to a cumulative load profile for the process chain and determine the embodied energy of a product. As different studies show, besides other relevant objectives (e.g. output) the specific energy and resource consumption behavior of a process chain can be significantly influenced by its specific technical configuration (design) and control [82]. This includes the individual selection/combination of processes/machines and their interlinkage (e.g. process chain structure, buffers) as well as aspects like batch sizes, scheduling of orders (e.g. start time, capacity allocation) or speed of production. Methods and tools for supporting an energy aware design and control of process chains are provided by [17,82,153,173,218,219]. An example for influencing the process chain energy demand through an organizational measure (in this case shifting of an order) is shown in Fig. 14 [163].

In general three different perspectives can be considered when talking about energy aware process chain design and control. Firstly, the electrical work can be reduced, for example by optimal utilization of equipment and avoiding energy waste in idling machines or the selection of appropriate machines for the specific manufacturing task. A second aspect, the avoidance of consumption peaks is an important issue. From an economic perspective, peaks should be avoided since they may cause cost surcharges in an electricity bill. However, peaks of consumption are also not favorable in context of dimensioning and control of supporting processes (e.g. the compressed air system) while this may lead to higher energy consumption at the end as well. Finally, another option – again rather from an economic point of view – is the shifting of consumption from day to night, because of less expensive energy price rates (e.g. base time at night) [199].

### 3.3. Process chain simulation

As pointed out above, the energy and resource consumption of process chains is rather dynamic depending on the state of the

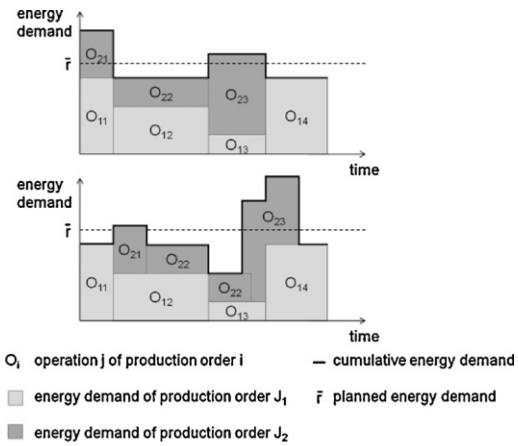


**Fig. 14.** Influence of PPC on energy demand [163].

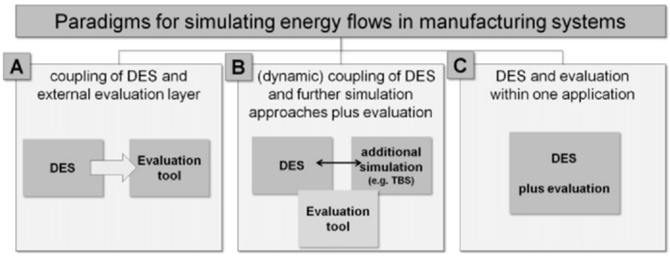


**Fig. 15.** Paradigms for simulating energy flows in manufacturing systems [86,196].

machines and their interactions. To cope with those dynamics when designing and controlling process chains, simulation is a promising approach [82,86]. Simulation can be used for single process chains and, if incorporating several chains and additional related aspects like technical building services, the factory as a whole (Section 4). Available commercial manufacturing system simulation tools do not consider these aspects yet. However, in research first approaches can be found (e.g. [45,70,79,90,92, 101,102,125,128,161,181,184,213,215,217,222]). They aim at augmenting material flow oriented discrete event simulation (DES) with environmentally relevant energy and resource flows. A comprehensive overview and discussion of those approaches can be found in [196]. In general three different basic paradigms can be distinguished, as shown in Fig. 15, which differ regarding the embedding of evaluation schemes or the interfaces with other simulation tools.

This inherent logic also leads to quite specific characteristics with distinctive advantages or drawbacks of each approach. Simulation approaches pursuing paradigm A offer relatively good coverage of manifold energy and resource flows, comprehensive evaluation schemes with relatively low modeling/simulation and good transferability. As a drawback, certain energy oriented dynamics and interdependencies cannot be considered in detail. In contrast, paradigm B allows very detailed analysis of different subsystems and fields of action, but leads to quite complex models which require knowledge and effort and are hardly transferable. Paradigm C as a 'one-stop solution' can basically overcome some drawbacks of the other paradigms. However, the user is potentially restricted by possible limitations of the utilized simulation environment which often do not allow combining the necessary logic to integrate dynamic energy consumption and the strong discrete event and material flow oriented perspective [86].

## 4. Factory level

Most studies and experience indicate that, to be complete, one must consider the operation of the factory, at a factory or plant level, as part of the efforts to reduce the impact and increase the effectiveness of manufacturing. Advances towards the next generation of manufacturing require the development and promotion of 'a holistic understanding of manufacturing' [93,94]. This requires the capability of holistic simulation involving technical building services and building climate, production machines/material flow, and production management, including production planning and scheduling. With this simulation capability, linking energy efficiency to the other important parameters in manufacturing is critical. Synergies should be identified and encouraged, for example better buildings, well optimized support facilities, effective maintenance, diagnostics, improved process quality, better safety and new service concepts, all the way up to new business models.

### *4.1. Factory level considerations*

#### *4.1.1. Defining levels of production in a facility – spatial and temporal*

A key requirement for insuring that analysis and optimization are actually effectively employed for planning and scheduling is to allow information to flow to where it is needed, e.g. for enterprise level and cross-enterprise optimization of energy consumption.

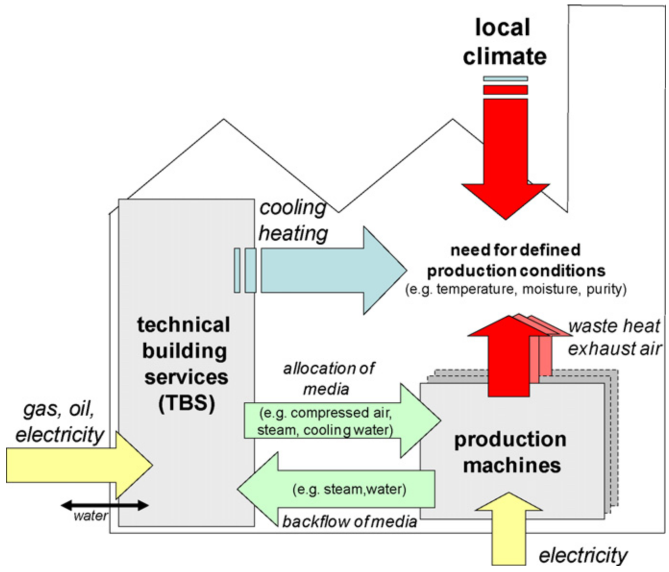


**Fig. 16.** Production facility as a complex control system [82].

The complexity and sophistication in the organization of manufacturing systems and processes necessitate a keen understanding of the organization for accurate environmental analysis. To assist in this effort, manufacturing can be broken into 'levels of study' across two orthogonal frameworks, spanning organizational and temporal levels.

The different levels of manufacturing systems as proposed by [165] were provided in the overview in Section 1.4. The primary focus here is on the third level – the facility. Herrmann and Thiede [82] present a holistic view on a production plant (facility) considering three main partial systems: the production system itself (with interlinked machines and personnel controlled through production management), the technical building services (TBS) and the building shell. The partial systems together with their dynamic interdependencies are shown in Fig. 16.

An equally compelling orthogonal view of manufacturing can be made based on temporal activities – through the design to manufacturing life cycle. This starts with product or process design, and continues through the design of the manufacturing process, process optimization, and finally post-process finishing and abatement. These temporal levels characterize a degree of control over the total environmental impact. They also affect facility level consumption and impacts. These four levels are as follows [165]:

- *Product design*: The earliest in design and manufacturing. At this stage there is the most opportunity to influence environmental impact and decisions throughout all future stages. At this level, critical decisions on part precision, materials, and design for assembly/recycling are made. Here there is scope to design the product as well as its manufacturing process to satisfy specific requirements in all applied criteria.
- *Process design*: The product design is fixed; however here a manufacturing process to suit this design is created. Flexibility to optimize the system is limited to known tools and processes that work with the specified design. Here there is extensive control over the performance of the process in all the criteria as allowed by the product design.
- *Process adjustments*: The basic manufacturing process is fixed but small changes to the process through process parameter selection and optimization are used to control the critical features such as precision, burr formation, and energy or consumable demand.
- *Post-processing*: Post-process finishing and abatement processes are used in controlling the part-precision and the environmental impact; at this level there is no control over the process as it has already been designed.

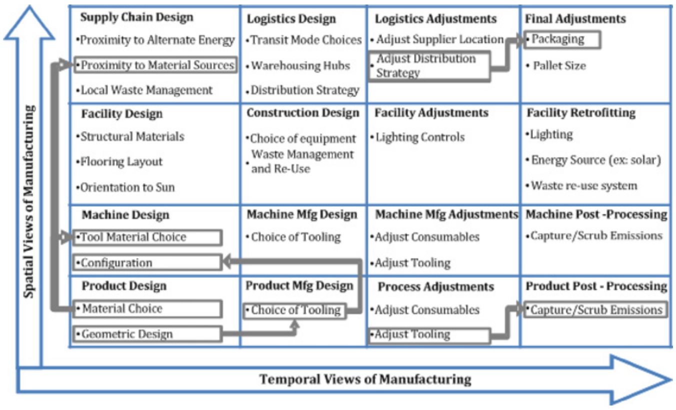


**Fig. 17.** An integrated view of manufacturing design levels and the decisions they contain. Arrows represent the flow of information from one decision to another. Adapted from [165].

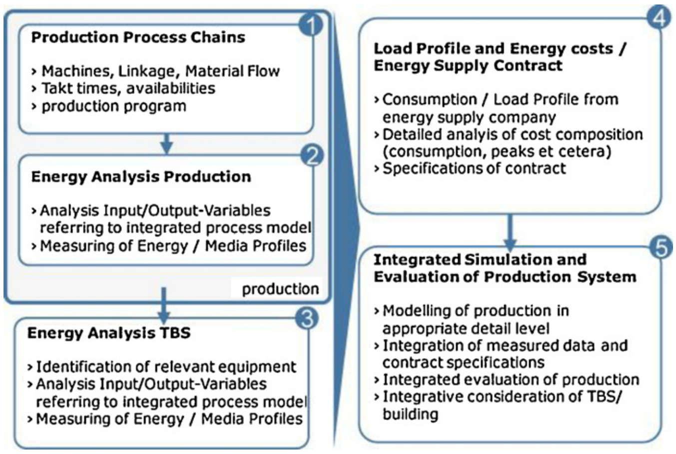


**Fig. 18.** Schematic of strategy for increasing energy efficiency in manufacturing companies spanning process to facility level consumption and impacts [82].

Fig. 17 illustrates the interaction between the temporal and spatial levels described by Reich-Weiser et al. [165]. Moving up and to the right in the figure means a loss of decision-making flexibility and, hence, an inability to control outcomes based on planning.

From these hierarchies – which span temporal and organizational levels – one can get a sense of the complexity involved in information capture and transfer in manufacturing systems. For effective decision-making, one needs to understand both what quality and quantity of information needs to pass between the levels and how decisions early on will percolate through the spatial and temporal levels.

The view shown in Fig. 17 points out two critical needs: firstly, factory wide planning and scheduling methodologies with the ability to accommodate complex interactions, and secondly and complementary to this, monitoring and data communication strategies and methodologies to be able to track the facility performance over these spatial and temporal axes.

*4.1.2. Production planning and scheduling at the factory level*

The literature on factory production planning and scheduling methodologies is rich. More recently, researchers have started addressing the inclusion of energy and other environmental metrics in the methodologies [57,82]. Herrmann and Thiede [82] point out that in addition to the energy consumed directly by production machinery, there are a number of building services that also account for energy consumption in support of production and the demand for higher productivity (cost, quality, and time) must be balanced with facility management energy optimization since the cost of energy can be high enough to alter the plan for best facility operation. This can be done by use of simulation tools according to a stepwise procedure.

Fig. 18, illustrates the procedure starting from the process chain level of detail, including cycle times and availability. Next, analysis of production machines with respect to all relevant energy and consumables input to or output from the machine (e.g. cooling water, compressed air, heat) are accounted for. The historic load profile for the facility and reality of pricing for peak and off peak energy consumption (electricity, natural gas, oil, etc.) are to be documented. Finally, taking into consideration the interdependencies of the machines, building and facility, the best operating environment and production plan can be determined based on simulation. The authors mention that some of the measures for energy efficiency may conflict with manufacturing target criteria like throughput or availability. Further work [195] describes the energy oriented manufacturing system simulation approach in detail. More examples of this methodology and a review of other related work were presented in [86].

Challenged by the potential conflict between process efficiency (time based) and factory efficiency (energy based), Fang et al. [57] propose a general multi-objective mixed integer linear programming formulation for optimizing a shop schedule. The method considers both productivity (e.g. make span) and energy (e.g. peak load and carbon footprint) related criteria. This new methodology considers the speed of operation as an independent variable, which can be varied to affect the peak load and energy consumption. This is most useful in situations in which the production machine tools often consume significant amounts of energy even in idle mode (and perhaps little additional energy when processing). So, idle time must be considered in the product flow determination.

Energy and resource utilization along the process chain for an automotive gear train manufacturing facility were studied by Schlosser et al. [175]. This included both the core processes (such as machining, heat treating, grinding, deburring, and washing) as well as the various resources provided to the chain by the facility (such as plant ventilation, water, electricity, and compressed air) and facility wide provision of consumables for such a high volume production operation (e.g. process water, central oil supply, nitrogen and other gases, and propane). The components of this production facility addressed were at the first three levels of manufacturing, corresponding to Sections 2–4 in this paper. The broader enterprise aspects were not included.

*4.2. Energy management: load control and peak load minimization*

The previous section described strategies for balancing energy, consumables and production constraints at various levels within the factory. To achieve this, the primary concerns are with energy management and, as a corollary, monitoring and control of energy consumption. The ability to actually manage these resources is dependent upon knowing the present state of consumption, historical consumption and the responsiveness of the system to changes (planned or otherwise).

One of the goals of facility energy management is minimization of peak load surcharges (cost-management) and the appropriate sizing of infrastructure and the power distribution as well as meeting constraints of infrastructure and technical building services (e.g. heating, ventilation and air conditioning). This requires data for process and system characterization as well as continuous monitoring. There are, not surprisingly, different approaches to this.

As mentioned in Section 2.2, Kara et al. [105] provide an up to date overview and background in the developments and challenges in electricity monitoring and metering systems and associated standards. Focusing on reducing the energy consumption of machine tools or other production machinery as a means for significantly improving the environmental performance of manufacturing systems, Vijayaraghavan and Dornfeld [212] proposed a methodology, based on a communication interface standard MTConnect for manufacturing, for monitoring energy consumption patterns in larger systems. It is vital to correlate energy usage

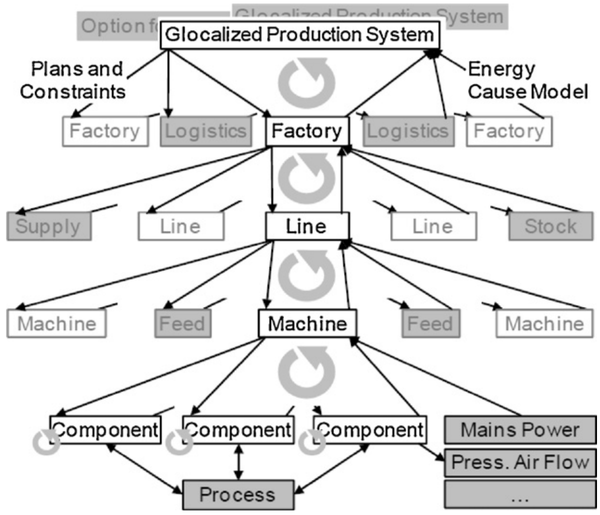


**Fig. 19.** Schematic of various energy control loops at the different levels of the facility [211].

with the operations being performed in the manufacturing system. However, since this can be challenging due to complexity of manufacturing systems and the vast number of data sources, event stream processing techniques were applied to automate the monitoring and analysis of energy consumption in manufacturing systems. The technique is extensible to all levels described above.

Adding a contextual aspect to the power demands in industry as part of industrial 'smart metering' was also proposed [87]. Energy consumption for various industrial processes varies dramatically and thus the time dynamic nature of process energy, and the energy of subordinate processes and machinery, must be understood. This can come from metering.

The event stream processing identifies trends in consumption of critical resources. Using trend analysis the consumption of electric energy, gas, compressed air, technical heat and water can be monitored, predicted and used to balance demand if that capability is present. For example, if the estimated workload is rising above a set maximum value within a given time period (e.g. 15 min), consumers with low priority (e.g. redundant machines or heating treatment furnaces with a high thermal capacity) can be switched off temporarily to meet the predefined limits.

One must either determine in advance the strategy for energy efficient operation of production systems through a priori optimization, or, if the architecture is capable thereof, process controls can decide if it is possible to reduce energy via local control and set components to energy-optimal states. Verl et al. [211] describe information flows that generate energy control loops at different levels based on model information, and propose a matching communication and control infrastructure. These mechanisms and control allow the use of models automatically and coherently on all required levels of detail and abstraction. The energy consumption model information is communicated only between the controls of a resource and sub-resources. Each control must understand the interdependencies with and within its direct neighbors. The system ensures that communication and computational loads are limited and balanced even for large systems. Fig. 19, from Verl et al. [211], schematically shows the various energy control loops that can be realized according to the proposed decentralized approach.

### 4.3. Factory design and operation influences

Diaz et al. [42] analyzed the energy consumption and $CO_2$ emissions for each life cycle stage of two milling machine tools in different environments. Besides the machine tool energy, HVAC and lighting of the working hall were found to be significant, consuming 40–65% of the total use stage energy.

Beyond the manufacturing floor and the production systems, the design of the factory, its physical layout, construction and traffic and material flow as well as location and insulation can have a large impact on the energy consumption for the structure containing the manufacturing operations.

Commercial software is available for comprehensive factory layout and process and material flow simulation (e.g. Autodesk Factory Design Suite, Siemens FactoryCAD and FactoryFLOW) help create more efficient factory layouts based on digital models of the factory. These tools allow engineers to analyze existing and proposed plant and system layouts for more efficient material flows and scheduling and routing in production systems. Energy, materials and other resource flows can also be tracked. Unlike the optimization tools discussed earlier in this section, these factory design tools are meant to compliment architectural design functions for a complete facility design.

The concept of life cycle management of production facilities was introduced [74] to address the design, installation, operation, adaptation and disposal of production facilities. Topics addressed in this research include maintenance, re-use or reconfiguring of production facilities or removal and reconstruction at another location. As with product life cycles, the life cycle of a production facility deserves attention.

#### 4.3.1. Energy efficient building technology

The term 'green factory' often refers to the factory buildings designed and built to minimize energy use and to recover resources [48]. Industrial buildings often consume and waste a huge amount of energy in terms of electricity and heat. In particular, when a factory or a building is designed as a new structure, energy efficient building technologies can easily be implemented. However, in existing buildings, small and inexpensive changes can lead to large energy savings and improve the energy efficiency of the whole building. A clear example of a factory designed to be energy and resource efficient, with respect to the building use, is the Ford Motor Company Rouge Plant [59].

The following impacts are recognized as significantly contributing to energy conservation.

The facades of a building have a number of functions including thermal and sound insulation as well as protection from humidity. In particular, thermal insulation for production facilities is not only important from a sustainability point of view, but also to provide thermal stability for the processing equipment.

Technically, the fenestration includes every opening in a building's outer shell, e.g. windows, doors and gates. The energy loss in heating or cooling through these openings can add up to 30%. In the last decade or so, windows have become much more sophisticated. Single pane windows have been replaced by double, triple or even quadruple panes. The layers are separated by insulating materials, as inert gases, to reduce their thermal conductivity. A low emissivity coating on the glass can reduce heat loss in the winter and prevent unwanted heat from entering in summer.

For production facilities, gates or material ports usually tend to cause the highest energy loss inside the fenestration, since they are oftentimes left open to permit a frequent and rapid material flow. Rapid action doors open and close rapidly for each crossing and therefore prevent energy losses. This effect can be enhanced if two rapid action doors are arranged consecutively as a lock.

The inside of a building should be illuminated as much as possible with daylight, since this is the most natural and energy efficient type of light. The minimum intensity of illumination cannot always be achieved only through daylight. Therefore, artificial lighting is often necessary. In order to reduce the energy consumption, a sensor, which measures the intensity of illumination, can be installed. A controller in connection with a dimmer regulates the artificial light such that the overall intensity of illumination is permanently above the minimum threshold.

#### 4.3.2. Example of 'green factory' technology – compressed air analysis

In a factory, compressed air is often regarded as the fourth utility, after electricity, natural gas and water, in facilitating production activities. In manufacturing plants, compressed air is widely used for actuating, cleaning, cooling, drying parts, and removing metal chips. However, the cost of compressed air production is one of the most expensive and least understood processes in a manufacturing facility [168]. The cost of electric power used to operate an air compressor continuously for a year (about 8200 h) is usually greater than the initial price of the equipment [107]. Per unit of energy delivered, compressed air is often more expensive than the other three utilities.

Besides the cost issues, compressed air production consumes a large amount of energy. In absolute terms it is estimated that about 3–9% of total energy consumed in the U.S. in 1997 is for air compression in manufacturing [35]. Yuan et al. [225] detail an example of compressed air use in automotive manufacturing facilities. Compressed air is used relatively indiscriminately in automotive manufacturing due to its ease of setup. There is no need for additional maintenance or special machines; the task can be accomplished by adding piping. In addition, as a form of energy, compressed air represents no fire or explosion hazard; it is clean and safe and often regarded as totally 'green' [32]. In a large production facility, plant air is the more typical supply and suffers from a number of limitations, including complexity of system, low efficiency (typically less than 60% of the total compressed air consumed contributes directly to the goods and services for which production was intended [60]; leaks are a major problem in plant air supply), energy storage limitations, unstable system pressure, and associated high cost. This low efficiency translates into excess energy consumption. The associated carbon footprint for energy use in providing compressed air was analyzed in [100].

Common supply patterns for compressed air include the following, plant air: the whole plant is supplied with compressed air from the air house, with pipes spread out in the plant to provide compressed air to all facilities, point-of-use: each machine is exclusively supplied by an independently installed air compressor, and local generation: a certain number of machines are grouped together and supplied by an air compressor.

An investigation of the compressed air supply methodologies to determine which of the three supply options mentioned above could be the most cost effective considering energy and related operating costs, including equipment purchase and operation, was performed for an automotive component production plant [225]. Compressed air in the facility studied was used to supply operating air to a number of CNC machine tools in the facility. An environmental analysis and a cost of ownership study were made for the alternative system layouts. The analysis found that a 'local generation' option would be preferable when compared with point of use and plant air options considering both cost and energy efficiency. Employment of local generation instead of plant air could potentially save $2000–$3200 dollars and 95,000 kWh each year on the CNC milling machines. Meanwhile, local generation offers numerous advantages over plant air with regard to reliability, simplicity, leakage prevention, and flexibility. Local generation is supplied by relatively short pipelines, which may lead to a significant reduction of losses due to leaks. Extra local compressors may be connected to the CNC machines in parallel, which automatically builds a great deal of redundancy into the system. Furthermore, the scale of local generation compressors enables greater flexibility as machines and processes change.

### *4.4. Lean and green production influences at the facility level*

Green manufacturing concepts are often linked to other lean practices in industry. Lean manufacturing is defined by Holweg [91] as a production practice that 'considers the expenditure of resources for any goal other than the creation of value for the end customer to be wasteful, and thus a target for elimination'. There are a number of approaches to 'lean'. The first approach is nominally the elimination of waste and uses tools that assist in uncovering waste in the process and system. A second approach is more aligned with the Toyota Production System (TPS), which focuses on the 'smoothness' of production and constructing a process with the capability to produce the required results by designing out process inconsistency (or 'muri'). This is to be done while trying to maintain as much flexibility as possible since excessive constraints or rigidity often induce waste (as in excessive set up/change over time or high minimum lot sizes, requiring extra inventory or inducing poor response to customer needs, i.e. poor response to 'pull'.)

As an example of the second type of lean manufacturing, Comau [29] recently introduced a 'smart assembly' cell focused on the production of high precision complex assemblies as in valve trains for auto engines. Citing the large number of individual machines and process steps used in traditional valve train assembly (some 72 parts in one case at a cycle time from 25 to 30 s per machine and several minutes per assembly in total along with a large capital investment), Comau's smart machine replaces the entire line by four operations and a total cycle time of 54 s. The cell, designed for 325,000 cylinder head annually, requires only 223 sq. meters of floor space compared to 753 sq. meters. Mori Seiki announced a similar system as well for a smart machining cell [135].

Although the Comau cell design was likely not motivated by green manufacturing concerns, the cell will have an impact on energy consumption by nature of the reduced number of stand-alone processes and, importantly, the tremendous reduction in floor space. And, since idle time is a big energy consumption concern in standalone machine tools, the higher utilization will reduce idle time.

One of the main tools for the first type of 'lean' is the Value Stream Map (VSM) – charting exactly the material and information flow in the system. Rother and Shook [169] define a value stream as 'all the actions (both value added and non-value added) currently required to bring a product through the main flows essential to every product: (1) the production flow from raw material into the arms of the customer, and (2) the design flow from concept to launch.' This can be a basis for introducing green manufacturing concepts to the enterprise. It starts with a very careful (and often tedious) assessment of the present state of the production system. This means outlining the processes and flow with the key interconnections and relationships, and collecting process data for each process. Examples of the process data include: cycle time, changeover time, uptime (on demand machine availability), production batch sizes, number of operators, number of product variations, pack size, working time (minus breaks), and scrap rate. Many of these characteristics have green implications, meaning they are predictors of energy or resource consumption – like cycle time, which can help define process energy, or scrap rate, which is an indication of efficiency of conversion of resources into products.

Although the procedures for VSM are well established, the use of VSM in green manufacturing analysis is not so well defined. The best approach is to use the concepts of VSM and lean to compliment the development and operation of efficient manufacturing operations with the requirements of reduced energy and resource utilization – leading towards green and sustainable manufacturing. If one reviews Ohno's 'seven wastes to be avoided' [123] and, realizing that this was developed before the current concern about the environment and green manufacturing was so commonly of interest, one can observe that many map directly onto green manufacturing practice. For example, the 'wastes' of producing more than is needed, or storing/inventorying more than needed, unnecessary transportation, unnecessary work steps or processes – all can be converted into wasted resources, energy, and other consumables or the indirect efforts of these wastes (such as floor space and HVAC costs, additional tooling and the manufacture and operation of it, unneeded raw materials and the associated imbedded energy, transport, storage and recycling).

## 5. Multi-factory level – industrial symbiosis

Moving a further step up the manufacturing hierarchy from the factory level, the interaction between industrial facilities comes into scope. This interaction may occur between suppliers and customers in the supply chain, as described in Section 6 of this keynote, but it may also occur between economically independent companies exchanging and utilizing flows of materials or energy to their mutual benefit, increasing the overall output from the given input of materials and resources compared to the situation where each facility would treat its waste streams in the conventional way, i.e. often just landfilling them. The mutualism in the interaction has led to the introduction of the term 'industrial symbiosis' from the examples of mutualistic symbiotic relationships between organisms of different species in natural ecosystems, in which these exchange flows of materials or protection for work in a way that is mutually beneficial.

### 5.1. Definition of industrial symbiosis

A widely used definition of industrial symbiosis has been formulated by Chertow [24]: 'Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity.'

The definition focuses on the fact that the industries are *separate*, i.e. cleaner production activities involving different departments or subsidiaries of one company are not considered industrial symbiosis (in the context of this paper these are covered in Section 3 at the level of multi machine ecosystems). The nature of the engagement is described in the definition as '*exchange of physical flows of materials, energy or water*'. In their discussion of Australian experience with industrial symbiosis, van Beers et al. [209] expand this point of the definition to include the joint use of utility infrastructure for energy or water production or wastewater treatment. The *geographic proximity* of the participants in the industrial symbiosis is emphasized in the definition, and indeed, most known examples of industrial symbiosis involve companies that are closely co-located. There are, however, examples that challenge this part of the definition in discussing the Australian minerals industry; Schwarz and Steininger [177] report on a large Austrian network of industrial waste recycling in the province of Styria, where some of the participants are at distances that necessitate transport of the commodities through pipelines or road transport. Chertow's definition also emphasizes that industrial symbiosis is a *collective approach*, meaning that several industries are normally involved. Again, the purpose is to distinguish the efforts beyond simple recycling activities, as carried out by scrap dealers for example. As a pragmatic way of deciding on this point, Chertow later writes: 'To distinguish industrial symbiosis from other types of exchanges, my colleagues and I have adopted a '3–2 heuristic' as a minimum criterion. Thus, at least three different entities must be involved in exchanging at least two different resources to be counted as a basic type of industrial symbiosis. By involving three entities, none of which is primarily engaged in a recycling oriented business, the 3–2 heuristic begins to recognize complex relationships rather than linear one-way exchanges.' [26].

### 5.2. Practical examples of industrial symbiosis

The most well-known example remains the industrial ecosystem constructed around a co-generation power plant in Kalundborg, Denmark (Fig. 20) [190]. Multiple flows are involved, but the main ones are centered around the exchange of energy flows and different qualities of water back and forth between power plant and the other main partners: an oil refinery, two biotech companies (pharmaceuticals and enzymes), and the municipality of Kalundborg (district heating for 5000 homes). In addition there are flows of flue gas treatment products between the power plant and a plasterboard producer (gypsum) and a local cement industry (fly ash), and between the biotech companies and local farmers (yeast slurry and sludge). On an annual basis, the exchange of

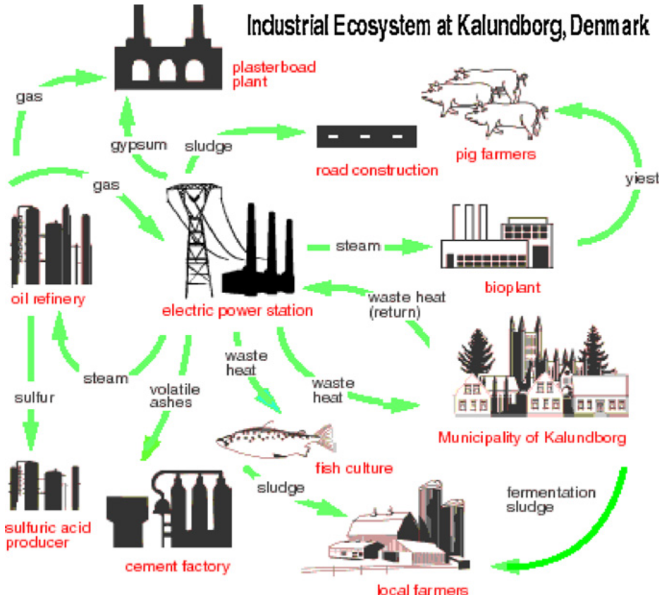


**Fig. 20.** Industrial symbiosis at Kalundborg.
Adapted from [190].

waste flows totals around 2.9 mio tons [26]. The roots of the industrial symbiosis collaboration at Kalundborg go back to the 1970s when some of the partners started collaborating on the reuse of water, but it was not until 1989 that the extent of the symbiotic relationships was realized, and the term industrial symbiosis coined.

Since then, other examples of industrial symbiosis have been identified or developed. A more comprehensive and geographically extended example is a network of collaborations that was discovered in the Austrian region of Styria in the 1990s, comprising a steel plant, power plants, paper producing industries, textile industry, cement industry and stone and ceramic industry as the main partners [177]. Examples from the mining and minerals industry in Australia focus on reuse of water, chemicals and mineral wastes [209]. Other examples are centered around forest and pulp and paper industries where residual products are used for energy production, and chemicals are recycled (e.g. [129,183]), or agro-industry systems like a Chinese example bordering between industrial ecology and supply chain integration. Here, an original sugar refinery activity has been expanded with industries using the two main by-product streams from the sugar production: spent molasses which are used in an alcohol plant, the residuals from which are used in fertilizing industry, and bagasse, the fibrous residues of the sugar canes, which are used in paper production [227,228].

In East Asian countries like China, Korea and Singapore, where formal planning is more institutionalized, and in the United States, industrial symbiosis typically occurs in the form of eco-industrial parks [26,124,228]. An eco-industrial park was defined for the U.S. EPA by the Field Book for the Development of Eco-Industrial Parks [127] as: 'a community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resource issues including energy, water, and materials. By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realize if it optimized its individual performance only'. In the United States the US President's Council on Sustainable Development, USPCSD in 1996 recommended that 'Federal and state agencies should assist communities that want to create eco-industrial parks that cluster businesses in the same area to create new models of industrial efficiency, cooperation, and environmental responsibility' [208]. At that time, 15 eco-industrial parks were planned in the U.S., but until now few, if any, have shown successful and lasting examples of industrial symbiosis [26].

### 5.3. Benefits realized through industrial symbiosis

It is clear that an industry will not voluntarily enter and remain in an industrial symbiotic relationship with one or more other industries if it does not entail clear economic benefits for the company. The economic benefits can be direct through:

- Reduced costs of raw materials on the input side, replacing costly virgin resources or materials by waste that is free or very cheap to acquire from the symbiosis network.
- Reduced costs for the treatment of waste streams (on the output side) as these are taken over by partners in the industrial symbiosis network.

In addition to these financial benefits, there are more indirect benefits through:

- Better access to and supply security for resources that are restricted. This is particularly the case for water, but in the future it is also potentially the case for waste flows containing other strategic resources like metals.
- Brand value, satisfying important stakeholders among customers, environmental regulators, local community members and employees [209].

For most companies, the economic and strategic benefits will be the drivers, but the question can be posed whether there are also environmental benefits, and if so, how large these are.

Industrial symbiosis typically allows an industry to substitute a high quality virgin resource (material, energy carrier or water) by a lower quality substitute (waste) that per definition is available in excess of demand in the region. This substitution involves three processes: conversion, substitution and avoidance [210].

- *Conversion* involves collection of the waste materials, energy or water from the symbiosis partner, processing into a suitable feedstock, and transport to the site of application.
- *Substitution* involves the use of the generated alternative feedstock, including possible adjustments of the process to compensate for lower quality inputs.
- *Avoidance* relates to the reduced or eliminated disposal of the waste that has been recovered.

The conversion processes entail overall negative environmental impacts as they require facilities, energy and possibly other resources and ancillary substances. Substitution, on the other hand, has indirect environmental benefits from helping to avoid resource extraction and processing, but it may also cause negative direct environmental impacts, since the use of lower grade inputs often requires more processing energy and produces more waste. Avoidance normally has only positive environmental impacts due to the reduced disposal of the avoided flows of waste or heat [210].

To quantify the environmental impacts of the industrial symbiosis, typically a comparison is performed to a reference system without industrial symbiosis. In this way, annual savings for some of the central flows of the industrial symbiosis at Kalundborg were quantified to 0.5 mio $m^3$ surface water, 23 mio $m^3$ of seawater and 1.3 mio GJ thermal energy (steam and hot water). In a similar approach, Chertow and Lombardi [25] demonstrated savings of both costs and effluent discharges for an industrial symbiosis involving substitution of oil-fired on-site steam generation in Guayama, Puerto Rico (USA), at a petrochemical complex by steam import from a coal-fired power station. Emissions of $SO_2$, $NO_x$, and PM10 were reduced, but emissions of CO and $CO_2$ increased.

The approach holds some methodological problems [210]: the benefits may be considered confidential and hence difficult to determine because they are commercially sensitive. The use of the stand-alone operation without symbiosis as reference scenario is questionable, particularly in the case of large streams of waste or by-products, where it is unlikely that disposal at high costs would continue in the case where no symbiosis were established. Typically, alternative solutions would be developed, eliminating or reducing the flow or finding other routes of utilizing the flows at lower costs or even commercializing them. Industrial development is full of examples on utilization of what was once a waste stream. Indeed, this kind of activity has been the nucleus around which several of the known examples of industrial symbiosis have grown. Finally, the net environmental impact of the symbiosis is determined as the sum of the impacts associated to the three processes, conversion, substitution and avoidance, including both direct impacts and indirect impacts from other activities induced elsewhere in society by these processes. In order to determine the overall benefit in terms of environmental impacts and resource use, there is a need to apply a life cycle perspective on the induced changes and identify any problem shifting to other parts of the involved product chains and between categories of environmental impact [18,75,183].

### 5.4. Hurdles and enhancers, constraints and concerns

Examining the existing examples of industrial symbiosis, it becomes clear that they are often constructed around one or a few central actor(s), with several more peripheral partners exchanging few and minor streams. In areas where industrial water is a scarce resource, the exchange and reuse of this resource can be a central element in the symbiosis. When a central partner is a power plant, some of the partners will typically utilize waste heat and steam from the power plant. Depending on the nature of the partners, other flows that are exchanged in the symbiosis will involve waste products, that can be reused and replace other resources for the users, often using (down cycling) organic materials as fuels in heat production. In the systems described above, examples of exchanged waste streams include gypsum, waste paper, textile waste, fertilizing sludge, used solvents, wood residuals and hydrogen gas.

The question can be posed which factors determine the emergence of industrial symbiotic networks. Boons et al. [18] proposed the following list of societal mechanisms for enhancing the development of industrial symbiosis:

- *Coercion*, forcing industries to adopt industrial symbiosis through legislation.
- *Imitation*, when industries adopt industrial symbiosis routines and concepts that they see in other industries for reasons of status or to deal with uncertain situations (e.g. access to resources).
- *Private interest government*, where a group of industries choose to collectively adopt industrial symbiosis voluntarily, because of the threat of legislation if they remain inactive.
- *Demonstration projects*, where policy actors initiate projects experimenting with industrial symbiosis, and actively spread the results as 'best practice' to accelerate its diffusion.
- *Training* and professionalization of individuals in the concepts and routines of industrial ecology who then subsequently start to apply these in their work environment.
- *Altering boundary conditions*, to stimulate actors within regional industrial systems to self-organize into industrial symbiosis networks.

While Boons et al. [18] put some faith in regulatory involvement in the development of industrial symbiosis, Chertow [26] is less optimistic in this regard. Comparing the US experience, trying to plan eco-industrial parks or industrial symbioses, with the Kalundborg symbiosis case, the author draws two conclusions on why the latter has produced a successful and lasting industrial symbiosis and the former not: 'First, we see that rather than resulting from planning or a multi stakeholder process such as the ones pursued through the U.S. President's Council on Sustainable Development, the Kalundborg symbiosis

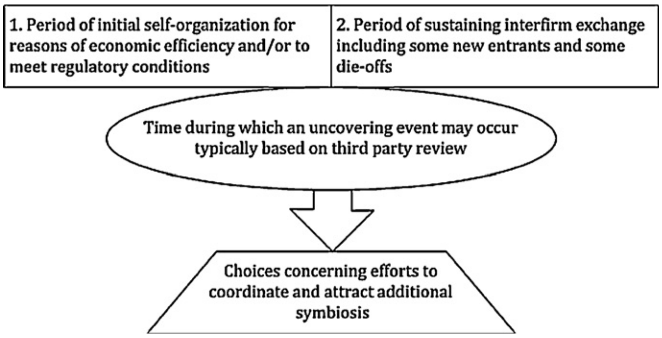


**Fig. 21.** The progression of industrial symbiosis relationships.
Adapted from [24].

emerged from self-organization initiated in the private sector to achieve certain goals., such as cost reduction, revenue enhancement, business expansion, and securing long-term access to water and energy. This implies that the symbiosis was not 'seen' by outsiders because the exchanges emerged from the invisible hand of the market rather than direct government policy or involvement. Second, once a revelation was made, a coordinative function was found to be helpful in organizing more exchanges and moving them forward'. Also in the Austrian and Australian examples of successful industrial symbiosis networks, there has been little active regulatory involvement in the development [177,209], and a conclusion seems to be that the industrial symbiosis is a difficult thing to plan and stage by policy measures. Chertow [26] concludes that '. . .many of the successful industrial ecosystems . . . did not arise in the ways pursued by the PCSD. One feature that several of these have in common is the experience of a quiet period where firms engaged in exchanges among themselves, unconscious of a bigger picture, followed by an act of discovery that revealed the pattern of existing symbiotic exchanges and the resulting environmental benefits'. In the Danish case however, the role of public policy cannot be completely dismissed since a rather ambitious environmental policy must have played a motivating role in the development of the Kalundborg symbiosis, with green taxation leading to high prices of both waste treatment and water extraction and later also energy. Building on the observation that a period of self-organization before being discovered as industrial symbiosis and marketed and expanded as such, was instrumental for the formation of the successful cases, Chertow [26] presents the model in Fig. 21 for the progression of industrial symbiosis relationships. She proposes a role for government and policy in:

- Help to identify and publicize already existing kernels of cooperative activity in the form or symbiotic relationships,
- Support such emerging kernels and help them expand by involving other industries in the region, and
- Provide incentives to catalyze the formation of new kernels by identifying promising precursors to symbiosis, but abstain from 'supporting projects, through public or private investment, that have much wishful thinking but no tangible kernels to roast' [26].

With its name derived from a biological analogy and its central role in the whole concept of industrial ecology [24], industrial symbiosis with its exchange of waste streams between independent industries would seem to be an important element in the way towards a more sustainable industrial society. But a relevant concern is whether the focus on exchanging waste streams moves the focus from a more traditional pollution prevention principle where waste should be prevented rather than treated and wasteful production processes should be substituted. And whether the contractually based exchanges of waste flows in this way serve to perpetuate a wasteful production rather than motivate development of cleaner processes that avoid the waste production altogether. At least it is clear that the economic performance of existing processes is improved by industrial symbiosis (otherwise this would not occur in the first place) and hence this important element in the overall incentive to introduce new and cleaner technology is weakened. In this way, industrial symbiosis has the potential to act both as a driver and a barrier for the development towards a sustainable industrial society, depending on the context and the nature of the involved industries.

## 6. Supply chain level

A supply chain can be defined as 'a set of three or more entities (organizations or individuals) directly involved in the upstream and the downstream flows of products, services, finances, and/or information from a source to a customer' [83,130]. In contrast to the organizational/spatial hierarchy covered in the previous sections, the focus here is on the provided good or service and its flow through the system. Transformation steps taking place in single companies/factories are therefore interlinked by transportation processes entailing environmental impacts and use of non-renewable resources. Based on this, sustainable supply chain management has been defined as 'management of raw materials and services from suppliers to manufacturer/service provider to customer and back with improvement of the social and environmental impacts explicitly considered' [143,158].

### 6.1. Country specific variables

Based on the definition of the manufacturing system and efficiency indicators, three major country specific factors with an influence on energy efficiency can be identified: climate, distances, and energy sources and associated price structure. Considered as national averages, other factors, such as worker qualification, degree of automation, age of machines, also significantly differ between countries. However, these factors are not dependent on geographic location. In contrast to the first set of factors, they are transferable and their actual state depends on the specific case of each manufacturing company.

#### 6.1.1. Energy source and energy cost

The different means of electricity production and provision vary strongly in terms of technology, use of fuels and impacts on the environment. Conventional thermal energy generation by incineration of non-renewable resources, such as coal or gas are among the most important contributors to emissions of greenhouse gases. Nuclear power generation contributes to the dispersion of radionuclides and increased background radiation in the environment and has unresolved problems with the storage of radioactive waste. Renewable sources, such as wind, water or solar power all tap the energy inflow from the sun. Wind and sun are not associated with any emissions in the use stage, but have issues like land occupation and visual impacts that influence their propagation. Hydroelectricity has impacts on riverine ecosystems and the creation of huge dams at hydropower stations causes submersion of existing vegetation that leads to substantial emissions of the greenhouse gas methane in countries like Brazil. Fig. 22 shows the energy mix composition for the electricity net generation in different countries worldwide [204].

Significant differences can be observed between countries largely depending on conventional thermal energy generation with certain high GHG emissions, such as Australia or Saudi Arabia, and countries that already mainly switched to renewable energy sources, like Brazil or Norway. Thus, energy consumption in specific countries is associated with a specific environmental impact depending on the sources.

The energy price is another important variable that needs to be considered in this category. As depicted in Fig. 23, since 2000 electricity prices show a steady trend upwards which is mainly caused by rising price of fossil fuels (e.g. oil and gas) [83].

Studies show that this general trend is very likely to continue in the coming years despite temporal fluctuations due to changing

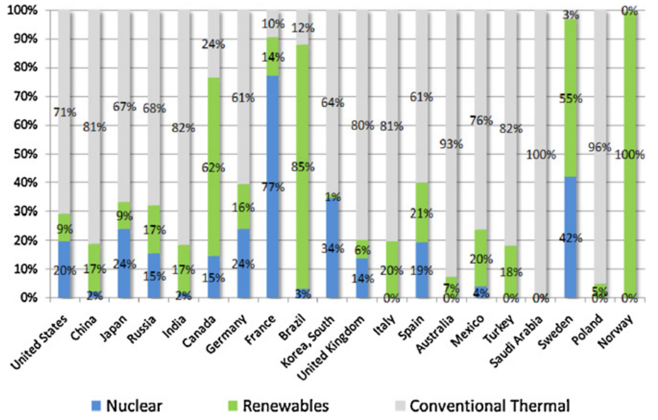


**Fig. 22.** Electricity generation in 2008 by type and country (top 20 countries) [204].

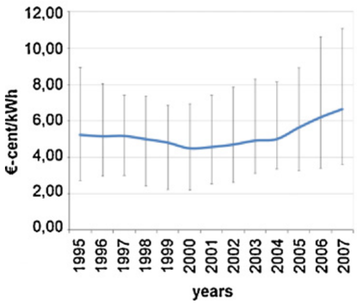


**Fig. 23.** Evolution of electricity prices in European countries [62,83].

economic conditions. However, Fig. 23 also underlines that energy prices strongly differ between countries due to the specific structure of energy supply (e.g. availability of energy sources), market conditions (supply/demand and competition situation) and political/legal background (e.g. taxes and subsidies). Therewith local energy prices are naturally a major location factor, which directly affects the cost structure of manufacturing companies.

*6.1.2. Transportation*

On the supply chain level, especially the distances to be covered during transport are of major influence for the energy consumption. This is realized using different modes of transportation, e.g. truck, rail, air, or ship. The input of these processes is mainly energy, i.e. the fuel for the different transportation modes. The output is on the one hand the transportation performance described by the mass of the freight transported over a specific distance. On the other hand, especially the use of non-renewable fuels is associated with emissions to the environment, such as $CO_2$ and other greenhouse gas emissions, and $NO_x$ and particulate matter with negative impacts on human health. Besides the freight task in terms of lot sizes and volume, especially the distances between the single actors in a supply chain and the mode of transportation are of particular importance for the energy consumption in supply chains. Actors within a supply chain may either be located within the same country as others, or in another country since single manufacturing steps are nowadays allocated globally based on availability and costs of resources, production factors, human resources and expertise as well as based on the location of markets and customers [28]. The specific fuel type and fuel efficiency of the chosen transport mode is a determining factor for the energy consumption in supply chains as well as the associated environmental impact. Furthermore, the location also determines available modes of transportation. An island location, such as Australia or Japan, allows only air or ship freight transport for international trade. On the contrary, international trade within Europe can mainly be conducted using domestic shipping, rail, and road transportation [83].

*6.1.3. Local climate*

Referring to the definition of the Intergovernmental Panel of Climate Change (IPCC), climate is 'the average weather or more rigorously the statistical description in terms of the mean and variability of relevant quantities over a period of time. These relevant quantities are most often surface variables such as temperature, precipitation and wind' [83]. Depending on the geographical location on the globe, the climate naturally differs between regions. In the case of air conditioned production, the local climate naturally has an impact on energy consumption of technical building services (TBS). For instance, while striving to keep certain production conditions constant, higher outside temperatures are likely to cause higher energy consumption for cooling. However, general statements about the actual effect are difficult to formulate as they strongly depend on the very specific case (e.g. dimension and isolation of building shell, configuration of TBS, actual progression of temperature and radiation, internal heat loads, as described in Section 4).

## 6.2. Global supply chains

In the context of global supply chains, the focus is not only on the energy efficiency of manufacturing systems, but also on the energy embodied into producing a product and the associated environmental impact. At this stage, a product life cycle view is critical since each product life cycle stage can be carried out in different geographical locations. Therefore, the aforementioned country specific variables may vary significantly along the product life cycle. As a result, 'embodied energy' is used more widely as an objective measure since the types of primary energy used may vary from electricity to coal and petrol [103,104].

In this context, there are two principal approaches to address the problem of including environmental impact considerations in supply chain design decisions. The first one is the extension of traditional supply chain design with environment as an additional objective. In this context, traditional business indicators, such as cost, time and quality are evaluated concurrently with the environmental objectives. Then multi-criteria optimization techniques are used to optimize the supply chain network design. Implementation in a company of the ISO 14001 standard [97] on environmental management supports the availability of data on environmental parameters and also gives requirements on the management of the supply chain [99]. Use of one of the existing LCA tools (e.g. SimaPro, Umberto or GaBi) may support estimation of the embodied energy and the associated environmental impact [75,116].

As a second approach, simplified input–output tools combined with detailed process LCA analysis can be used to evaluate the embodied energy of different manufacturing supply chains [104]. Later, other objectives can be added, such as time and cost, in order to do trade-off analysis in between various conflicting objectives.

One of the challenges of process LCAs is the so-called whirlpool effect caused by (nearly) infinite feedback-loops in the system. As an example, production of manufacturing equipment requires energy (e.g. coal), but to produce this energy manufacturing industry is needed to produce tools that can be used to extract the fossil fuels and so forth. Modeling of these loops typically involves a cut-off after a few iterations, but at the macro-economic level, statistical input–output analysis (IOA) is a powerful tool to include whirlpool effects between the different sectors of the economy in the analysis of the impacts from industrial production.

Input–output analysis in the current form was founded by Leontief [120] on the basis of Quesnay's concept 'Tableau Economique' [159]. The method describes and analyzes the interactions among different sectors of a network [188,200]. In this network, a general equilibrium model of all components of a given economic system is formulated. The interdependence among the different parts of a given system is described by a set of linear equations [115]. Leontief's original method considered only the monetary flow from a given amount of output backward to the input and it is used for the examination of economic activities [11,50]. In recent years, through various scientific contributions, the economic input–output tables have been combined with information on resource use and environmental emissions linked to the economic flows to support analysis of the environmental impacts of different sectors of the economy [19,55,76,118,132,224]. The environmentally enhanced input–output analysis (EIO) has the strength of solving the whirlpool effect but the quality of the environmental information is deficient for many environmental impacts. The emission of $CO_2$ is one of the best covered aspects and this has been used to investigate the consequences of moving production from industrialized nations to developing countries such as China [89,122,180].

Another possible approach is to use a hybrid of product LCA and EIO analysis [164]. In this case, a matrix approach can be used to determine what needs to be measured (either time or cost and either green or sustainability), what was the geographic scope (local, regional, or global scope), and what was the manufacturing scope (product, machine/device, facility/line/cell, supply chain, or life cycle scope). Then the iterative financial hybrid life cycle assessment (LCA) can be used in order to set up key areas as contributors to the GHG emissions and to estimate the electricity emissions in a particular location while the transportation emissions of goods between locations can be estimated by multiple sources.

## 7. Conclusions

A wide variety of considerations with relation to environmental impact reducing measures in general and energy and resource efficiency in specific has been discussed and identified methods and techniques for analysis and system optimization reviewed. At each system level a number of generic conclusions can be drawn.

For the *unit process level* it can be concluded that:

- Redesign of machine tools and selective control can significantly increase the energy efficiency without affecting productivity. Case studies illustrate improvements with a factor 1.2–3. The obvious lack of priority for energy efficiency among machine tool builders leaves on average substantial space for improvement requiring only well-known methods and techniques.
- When allocating machine tools during process and production planning, an appropriate choice at near nominal capacity level is highly recommendable. Case studies demonstrate an influence on the energy requirements of up to a factor 2.
- Optimization of process parameter settings and well optimized control allow to reduce the energy consumption. A factor 1.1 is a typical order of magnitude of the achievable improvements.

For this level systematic impact assessment methods have been developed that allow to expect systematic data collection and LCI database contributions over the next decade. This forms a first step towards transparency in comparison of machine tool environmental efficiency and ultimately a machine tool eco-labeling system. External visibility of achieved efficiency levels through such label should help to motivate machine tool builders to work towards more energy and resource efficient solutions.

Related to *multi-machine systems* the following major conclusions can be formulated:

- Energy and material resource reuse opportunities can often be identified through exergy cascading strategies. Examples with a factor 1.2 efficiency improvement have been reported. However, this strategy has not yet been extensively explored.
- Peak power and total energy consumption can be minimized by means of planning and optimization methods supported by simulation techniques.

At the *factory level* important conclusions are:

- When exceeding the level of multi machine chains, simulation techniques become predominant to master the complexity of predicting energy and resource flows for larger manufacturing systems.
- Technical building services can consume considerable amounts of energy: it is obvious that factory layout and facility optimization need careful attention in a design stage.
- Just like residential buildings, production facilities need to be constructed according to state of the art building physics principles, thus minimizing energy inputs for HVAC conditioning of the work environment, while taking into account local climate conditions.
- Similar to the multi-machine strategy, production planning can be optimized at a facility wide level in order to limit the total energy consumption.

At *multi-facility level* the following conclusions can be drawn with respect to industrial symbiosis opportunities:

- The geographic co-location of production plants with possible synergies in terms of waste streams facilitates the exchange of the physical flows that are involved. As such industrial symbiosis may help to reduce industry's need for treatment of solid and liquid waste and increase the overall efficiency both in terms of energy and material resources.
- Reported industrial symbiosis examples indicate that the principle has mainly been tested in process industry and is hardly recognized in discrete manufacturing sectors.
- The focus on exchanging waste streams may increase the risk for reduced attention for traditional pollution prevention activities aiming to avoid the generation of waste in the first place, e.g. through internal recycling.
- The most effective way of strengthening industrial symbiosis is to increase the economic motivation. Regulatory means thus include taxation of the use of virgin resources and higher fees for the treatment of waste.

Considering the *supply-chain level* the choice for specific production locations clearly influences the energy embedded in a product and the related environmental impact:

- While beyond the control of individual manufacturing companies, regional electricity generation practices have a major influence on the environmental impact associated with manufacturing operations (a factor 6 between countries with minimum and maximum impact of average electricity generation impact can be observed).
- The production location also determines the need for transport of raw materials and finished products as well as the transport mode, resulting in corresponding energy demands.
- Depending on the type of operations performed, local climate conditions can significantly influence the energy need.

It is obvious that the different opportunities for efficiency improvement identified at the respective distinguished levels can be combined in an integrated effort for impact reduction and economy improvement. However, the possible measures are not mutually independent: energy or material resource saving measures at unit process level will, for example, typically result in a decrease in possible energy reuse at multi-machine level. An overall reduction in electrical energy consumption will reduce the impact of choice of location for a production facility in absolute terms.

Most of the demonstrated available technological solutions for efficiency improvement only require well-known engineering methods for implementation. The authors conservatively estimate that combining such techniques with the reviewed intelligent planning and control optimization methods, offers a potential for global energy consumption reduction in manufacturing with at least 50%. A thorough optimization effort at all considered levels could result in more substantial improvements though. It is evident however that the replacement of machine tools and the redesign and upgrading of facilities this will require cannot be expected to happen overnight. Furthermore, the impact of the manufacture of investment goods itself should be taken into account when considering early replacement of existing infrastructure.

As a general recommendation for further research, the authors observed a significantly less intensive research activity with respect to resource efficiency utilization in comparison with the attention spent to energy efficiency. Taking the non-continuous nature of discrete part manufacturing and the time independency of material reuse options into account, material efficiency improvement still offers substantial research potential.

## Acknowledgements

The authors want to explicitly acknowledge the input received from numerous CIRP colleagues and from researchers in the $CO_2$PE! community. The authors want to acknowledge the support of IWT-Vlaanderen through its PhD grant no. 091232.

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