# L

## Lapping

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### Synonyms

Free abrasive machining; Loose abrasive machining

### Definition

Lapping is an abrasive machining process in which abrasive grains dispersed either in a paste or a fluid are applied to the moving surface of an opposing formed tool (the lap) so that the individual grains follow a disordered path (DIN 8589).

### Theory and Application

#### Introduction

The manufacturing process "lapping" is used to produce functional surfaces of highest geometrically defined shape and having optimum conditions of surface quality. According to DIN 8589, lapping is part of the group of cutting with geometrically undefined cutting edges, and it is suitable for processing almost every material. Lapping is increasingly used to process workpieces with sealing function, high geometrical precision, as well as workpieces which show characteristic crater surfaces (Spur and Stöferle 1980).

In principle, the process could be divided into lapping without and lapping with a shaped counterpart. Lapping without shaped counterpart, for example, the lap blasting, inclines the optimization of the surface topography of the workpiece. Contrarily, lapping with shaped counterpart leads to a higher material removal rate. Workpiece and lapping tool, made up of shaped counterpart and lapping mixture, move toward each other in preferably disordered paths with many directional changes. The loose abrasive, which is distributed in the lapping mixture, is introduced into the contact zone between counterpart and workpiece stochastically and temporally. Due to the lapping pressure, caused by the shaped counterpart, material removal occurs whereby mostly undirected, so-called isotropy, surface textures arise. The advantages and disadvantages of this process are listed in Table 1.

Concerning the cutting mechanism, there are differences between processing ductile, metallic materials and brittle hard materials such as glass or ceramics. In case of ductile materials, microplastic deformations of surfaces, hardening, and embrittlement as well as breakaways of particles rather appear. When processing brittle hard materials, micro cracks are induced and crack systems occur, which lead to breakaways of particles (Fig. 1). The structure of the workpiece surface is significantly influenced by the applied lapping


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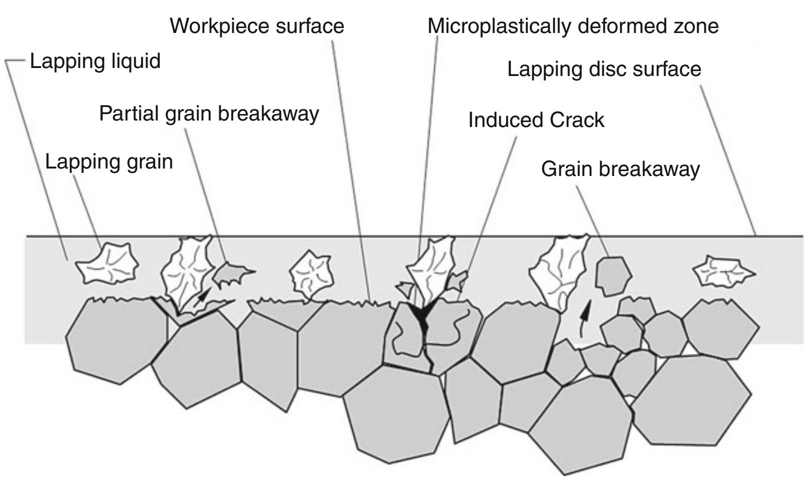
pressure, lapping grain size, and the relative velocity (Spur et al. 1989).

## Tool: Lapping Mixture

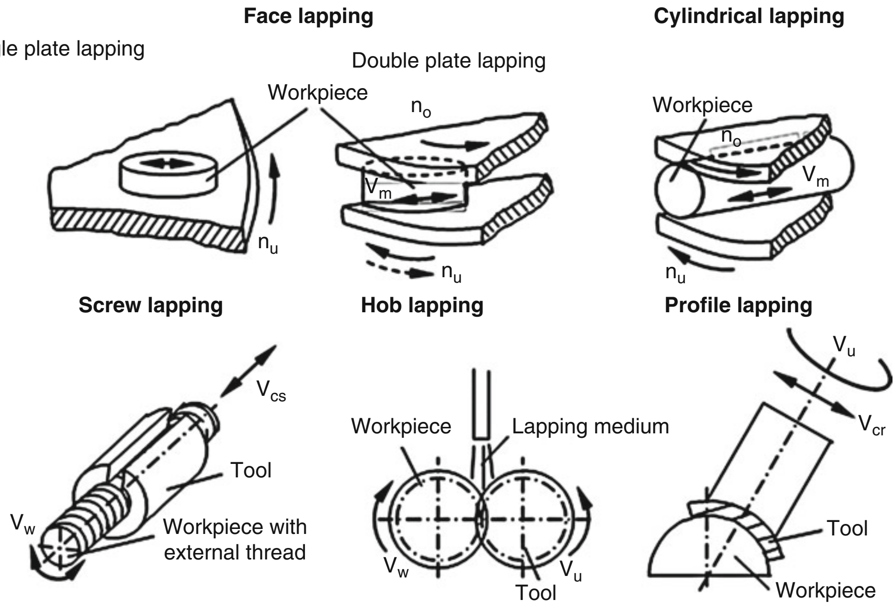
The choice of material of the shaped counterpart depends on the material which has to be machined. According to the case of application, tools of cast iron, copper, aluminum, or even glass are used. The lapping medium is composed of the lapping emulsion, a liquid or a paste, and loose abrasive grains, which are allocated in the lapping mixture. A criterion of the quality of the lapping mixture is among others a good miscibility (no agglomeration, no early settling). Oils and mediums made of paraffin, Vaseline, petroleum, or other impurities are used as the carrier mediums. Lubrication is not necessary, but transportation of the chips out of the contact zone safely and sufficient cooling characteristics are necessary. Furthermore, the application of too high-viscosity compounding could lead to a non-effective machining process. On the other hand, a low-viscosity suspension could be the trigger for damages caused by cold welding between the workpiece and the lapping tool. Usually, the used lapping grain is composed of aluminum oxide, silicon carbide, or boron carbide, and, in some cases, diamond (because it has to be principally harder than the workpiece material). In order to produce high-quality functional surfaces, the combinations of aluminum oxide for soft steel and cast iron, silicon carbide for alloy steels as well as boron carbide, and diamond for hard materials like ceramics appeared to be convenient. With coarse grains, the material removal rate increases (rough lapping). To accomplish better surface qualities, it is common to run the machine

**Lapping, Table 1** Advantages and disadvantages of lapping

| Advantages | Disadvantages |
|---|---|
| Possibility of processing almost every material and part size | Disposal of the lapping sludge as special waste |
| Short changeover time as well as low costs for workpiece holders | Comparatively low removal rates at high wastage of grain |
| Processing several workpieces in one operation cycle of the machine | Necessity of final cleaning of workpieces |
| Undirected process traces and isotropy surface structures | Processability only of basic geometries of workpieces |
| Minor action of heat, therefore no deformation or changes in structure of the processed workpieces | |
| Tension-free mounting of workpieces | |
| Generating precise functional surfaces with exceedingly shape precision on flatness and plane parallelism | |




**Lapping, Fig. 1** Material removal caused by grains




**Lapping, Fig. 2** Main groups of lapping according to DIN 8589 part 15

a second time with finer grains and corresponding lower material removal rate (Marinescu et al. 2006; Sabotka 1991; Uhlmann and Ardelt 1999).

## Applications

According to DIN 8589 part 15, the lapping procedures with shaped counterpart are divided into four groups, namely, the generated surface, the kind of surface, the kinematic of the material removal process and the form of the tool profile (Fig. 2). Besides the screw, hob, and profile lapping, there are two main lapping procedures called face and cylindrical lapping, which are explained in detail in the following.

Face lapping is used to process flat workpieces and to produce functional surfaces with highest standards in geometry and surface quality. At the double-face lapping, two parallel flat surfaces are processed simultaneously with minor measure diversification and tight measure tolerances. A typical field of application is the processing of bearing rings. A characteristic is the relative movement of the workpieces on cycloid trajectories caused by the special kinematic (Marinescu et al. 2006; Uhlmann et al. 1998).

External cylindrical lapping is used to process external surfaces of cylindrical parts. Therefore, the workpieces are mounted radially on a workpiece holder on a two-face machine, whereby the parts scroll with an eccentric motion between the lapping disks. This process is used to reach very high shape precision, required, for instance, for jet needles in injection pumps. Cylindrical lapping of drilled holes is realized with cylindrical bushes, which describe rotating and lifting movements. Because of this kinematic, high surface qualities are reached, which are unable to be accomplished by other processes (Paulmann 1991).

## Cross-References

► Grinding

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# Laser Ablation

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## Synonyms

Sublimation; Vaporization

## Definition

Laser ablation describes a material removal mechanism in which a material is removed in gaseous state directly from a solid state by irradiating it with high optical intensities.

## Theory and Application

Laser radiation consists of electromagnetic radiation with an electric field ($E$) and a magnetic field ($H$). The absorption of radiation in materials is done via excitation of electrons (free or bound) inside the bulk material. Interaction will only take place with electrons of the atoms, since the nucleus weight is too large to follow the high-frequency laser radiation field. According to Dahotre and Harimkar (2008), the following set of equations describes the effects of linear absorption mechanisms for materials like metals or graphite. The imposed force on the electron can be described as

$$F = eE + e\left(\frac{v}{c} \times H\right)$$

where $e$ represents electron charge, $E$ the electric field, $v$ the electron velocity, and $c$ the speed of light. The absorbed energy leads to heat generation inside the material due to the excitation energy of bound electrons or the kinetic energy of the free electrons. In the case of metal materials, this leads to lattice vibrations due to electron-lattice collisions in case of free electrons, which will carry heat into the material by heat conduction. Absorption of laser radiation in the material can be written as (Beer-Lambert law)

$$I(z) = (1 - R) I_o e^{-\mu z}$$

where $R$ is the reflectivity, $I_0$ is the incident intensity, $\mu$ is the absorption coefficient, and $I(z)$ represents the intensity at depth $z$. The significant absorption depth can be written as (Craig and Welch 2001)

$$L = \frac{1}{\mu}$$

The absorption of laser radiation in opaque materials can be calculated as follows:

$$A = 1 - R$$

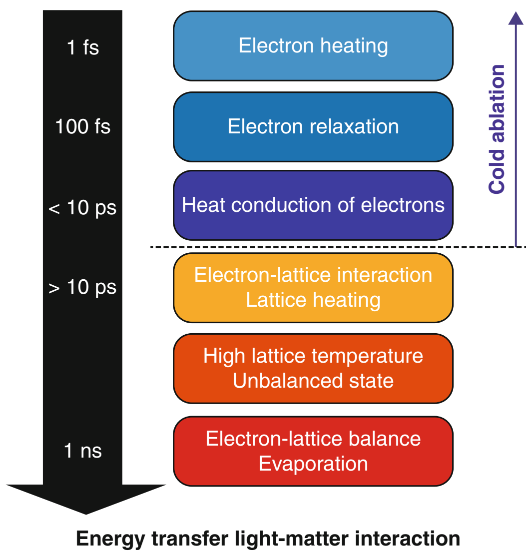
$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}$$

$$n_c = n - ik$$

where $A$ is the absorption, $R$ is the reflection, $n$ and $k$ represent the refractive and extinction coefficients, and $n_c$ is the complex refractive index. The parameters $n$ and $k$ are the real and complex parts of the refractive index, and these strongly depend on wavelength and temperature and are therefore important factors in laser-material interaction. Laser ablation depends strongly on the absorption characteristics of the material (absorption coefficient, ablation threshold), the pulsewidth, and the wavelength of the used laser system. While for transparent materials very large intensities are required to excite electrons across a large bandgap, the threshold fluence (energy per area) in absorbing materials can be considerably lower. In the latter case, pulse durations in the nano-, pico-, and femtosecond time regime can be used. Thermal ablation characteristics are dominant in the case of nanosecond pulses going well into the picosecond pulsewidth regime (athermal processing starts at a pulsewidth of about $t = t_{ep} = 10$ ps where $t_{ep}$ stands for the interaction of the electron and the phonon system). Material removal is accomplished by heating to the melt and then into the vapor aggregation state. Transformation processes are homogenous nucleation of gas bubbles in a metastable liquid such as phase explosion or explosive boiling, phase separation of a mechanically unstable liquid by spinodal decomposition, and normal vaporization of the outer surface. In photochemical ablation, the breakup of molecular bonds is driven by strong, tensile pressure waves which lead to spallation in solids and cavitation mechanisms in liquids and dissociation of a homogeneous, supercritical fluid into clusters upon dilution in vacuum, such as fragmentation (Lewis and Perez 2010). The pulsewidth dependency can be categorized in different ablation regimes for linear absorbing matter as listed below (Gillner et al. 2011):

- Absorption of optical energy by quasi-free electrons $t_\gamma < 10$ fs
- Thermalization of the electrons called electron system $t_{ee} < 100$ fs
- Interaction between the electron and the phonon system $t_{ep} < 10$ ps
- Thermalization of the phonon system $t_{pp} < 100$ ps

The corresponding pulsewidth is denoted by $t_{xx}$ where "$xx$" represents each interaction time regime. These critical pulsewidth regimes are not sharp edged but rather define a transition region in which ablation characteristics change from one mechanism to the other. Absorption characteristics in dependency of the laser wavelength are also strongly influenced by the used pulsewidth. Whereas an optically transparent material such as glass is transparent for a wavelength in the visible regime using a pulsewidth of nanoseconds, it can be processed using pulsewidths below 10 ps into the femtosecond regime. Another example for the pulsewidth dependency, for metal materials, is shown in Fig. 1. Another possible absorption characteristic is multiphoton absorption. For matter with absorption bands in the deep ultraviolet, moderate intensities



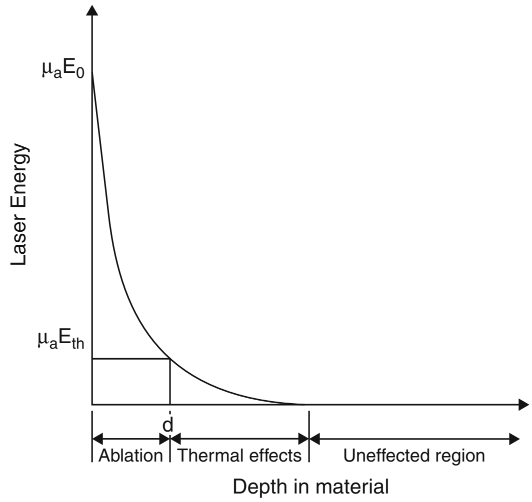

**Laser Ablation, Fig. 1** Pulsewidth ablation regimes in pulsed laser ablation in the case of metals will not lead to ablation by a one-photon process. Within this mechanism, two or more photons in the visible and infrared region are absorbed at the same time, which has the same effect as a deep ultraviolet photon with an identical energy level (Gillner et al. 2011). Since photon energy needs to be higher than bond energy in order to break the molecular bonds of the material, ultraviolet radiation would provide these required energies. If photon energy cannot exceed the required energy level but two or more photons are absorbed at the same time, the total incident energy can exceed the molecular bond energy. Therefore, fragmentation of the workpiece can take place.

Modeling laser-material interactions between continuous wave and nanoseconds is a complex problem, requiring modeling of melting, boiling, and vaporization phase transformations. Material removal is done by ejection of molten material or vapor which is done via a plasma plume which is already present while irradiation still occurs. Therefore, a part of the irradiated energy is dissipated in the vapor plume, thus making the process less efficient. Thermal modeling can be done as a one-, two-, or three-dimensional heat conduction problem. Therefore, a detailed description of these effects will not be given here. In laser ablation, one important characteristic is the thermal penetration depth, which is given by

$$\delta_{\text{therm}} = 2\sqrt{\frac{\kappa t_p}{c_p \rho}}$$

where $\kappa$ is the thermal conductivity, $c_p$ is the heat capacity, $\rho$ is the mass density, and $t_p$ represents the pulse duration. Dahotre et al. describe the ablation model as a "blowoff" model which assumes that a material is removed if an ablation threshold $\mu_a E_{th}$ is reached; here $\mu_a$ is the material absorption coefficient, and $E_{th}$ is incident ablation threshold laser energy. Figure 2 presents a representation of absorbed energy distribution if a material is irradiated with incident laser energy $E_0$.

In the case for femtosecond pulsewidths, a two-temperature model is used. Here, decoupling of the effects of the electron and the phonon system takes place. The two primary equations are




**Laser Ablation, Fig. 2** Distribution of absorbed laser intensity in the depth of material (Dahotre and Harimkar 2008)

$$c_e \frac{dT_e}{dt} = \frac{\partial}{\partial z}\left(\kappa_e \frac{\partial T_e}{\partial z}\right) + S - \mu\left(T_e - T_p\right)$$

$$c_p \frac{dT_p}{dt} = \mu\left(T_e - T_p\right)$$

where $C_e$ and $C_p$ are the heat capacities of the electron and the phonon system, $\kappa_e$ is heat conductivity of the electron system, $S$ represents the incident optical energy, $\mu$ is the electron-phonon coupling constant, and $T_e$ and $T_p$ are the temperatures of the two systems. One of the major differences between the short and ultrashort laser-material interaction is the time dependency on energy deposition into the material. Whereas in continuous down to nanosecond laser energy deposition takes place while the laser pulse is incident on the material, in the pico- to femtosecond range energy, deposition takes place a certain time after the laser pulse is terminated.

Laser ablation finds applications, for instance, in micromachining and nanomanufacturing, in cases where feature sizes in the micro- and submicrometer range are required. It is also applied in surface processing and patterning, e.g., in patterning of biomedical devices. Moreover, this technology is suitable for processing polymers, precision removal of tissues, and film deposition, among others.

## Cross-References

▶ Laser Beam Machining
▶ Micromachining

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# Laser Beam Machining

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## Synonyms

Laser Beam Processing

## Definition

Removing, joining, modifying, or adding materials by high-intensity electromagnetic radiation with wavelengths in the optical regime (100 nm–1 mm)

## Theory and Application

### Introduction

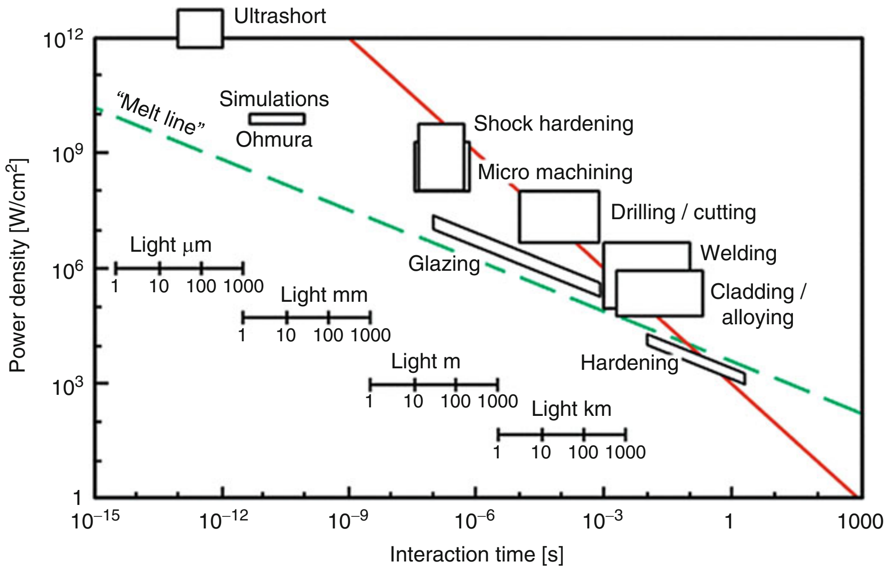
Laser beams are highly directed, coherent, and monochromatic waves of electromagnetic radiation in the spectral range between ≈100 nm (far UV) and some hundreds of micrometers (far IR). The term "laser" is an acronym for the physical effect (light amplification by stimulated emission of radiation) but is often also used to refer to the beam source. The first laser was demonstrated in 1960 by Th. H. Maiman, and it has since then been developed into various fields of applications, e.g., production engineering, medicine, measurement, science, and data recording.

Due to the high focusability, laser beams can generate very high irradiation intensities which make them a suitable and wear-free tool for production engineering. By proper choice of processing parameters, such as intensity, wavelength, mode of operation (continuous wave or pulsed), and process additives, various physical effects can be triggered, depending on the optical and thermal properties of the processed material. Therefore, the range of possible applications is broad: The main applications in production engineering are welding, cutting, drilling, micromachining, material modification, and additive processes.

Typical beam sources for production engineering are based on solid state or gas lasers. Within the group of solid state sources, Nd:YAG (yttrium aluminum garnet crystal doped with neodymium), neodymium-doped glass, and $Al_2O_3$ (ruby) are widely used as laser media. The most common gas lasers are $CO_2$, HeNe, and excimer (excited dimer) lasers. Most commercial applications use pulsed lasers (see Pulse) with pulse durations between some seconds down into the nanosecond regime. In the recent years, ultrashort pulsed laser sources with pulse durations in the pico- or femtosecond time regime entered commercial markets, especially for precision machining. An overview of laser machining processes is given in Fig. 1.

### Cutting

Laser cutting is the most widespread laser-based manufacturing process in industry. In fusion cutting, a focused laser beam with an intensity $>1$ MW/cm$^2$ melts the material which is then driven out of the cutting kerf by a nitrogen or argon gas jet. This gas jet is formed by a nozzle




**Laser Beam Machining, Fig. 1** Overview of laser machining processes and their typical laser-matter interaction times and power densities. The red line marks the 1 kJ/$cm^2$ energy density level, where most processes are distributed. The dotted line indicates the melt boundary of metals. (Reprinted from Meijer et al. 2002, with permission from Elsevier)

and aligned coaxially to the laser beam. Differential pressures of about 3–20 bar are applied leading to a supersonic gas flow at the nozzle exit. Thus, the focusing optic is protected from sparks produced by the cutting process. For oxygen cutting, an oxygen-containing assist gas is used. It provides additional energy from an exothermal reaction and allows for a higher cutting speed up to six times compared to fusion cutting. This is accompanied by decreased cutting quality. Sublimation cutting differs from the aforementioned methods by the absence of melt ejection: The material in the cutting kerf is directly transferred to the gaseous state due to comparatively high radiation intensities. An inert assist gas is used to only protect the focusing optic. Mainly flatbed systems with $CO_2$ lasers are used for cutting sheet metal, whereas 3D contours are usually cut with Nd:YAG or fiber lasers since their radiation can be guided through an optical fiber (Figs. 2 and 3, Tables 1 and 2).

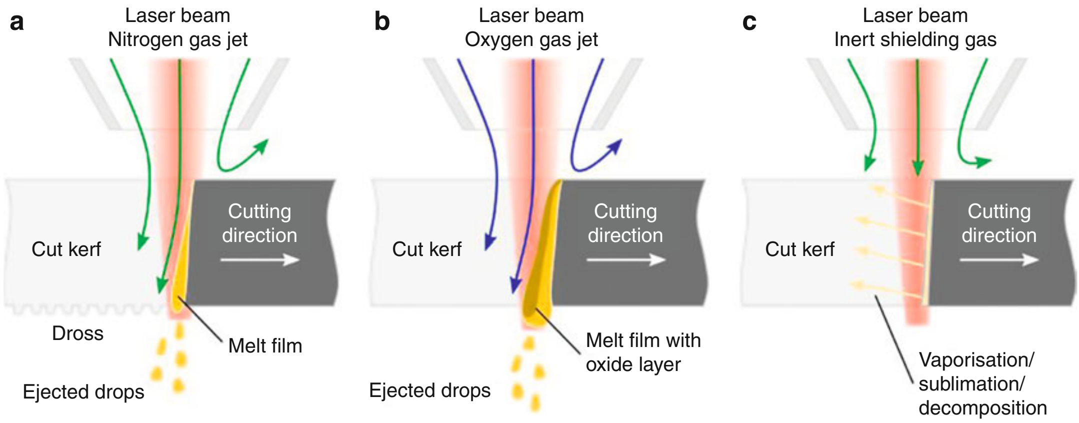
## Joining

Using laser radiation, a large variety of materials can be joined. For metals, depending on the applied power intensity and feed rate, it is distinguished between heat conduction welding (generally $I < 0.1$ MW/$cm^2$) and deep penetration welding, which forms a keyhole during the process. Apart from metals, also glass and thermoplastic polymers can be joined. More information can be found in the entry Laser Welding.

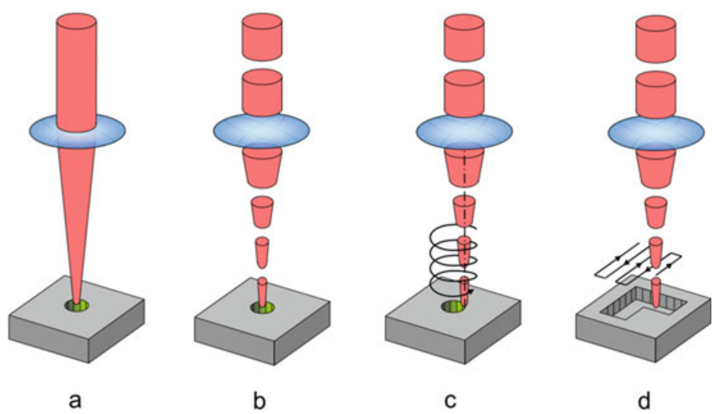
## Drilling and Ablation

With laser beams, materials can be precisely removed in a noncontact and reproducible manner. With the ability to drill or machine a variety of materials, including metals, polymers, and ceramics, as well as composites and thin films, laser beams can be an efficient and economical tool in a number of industrial applications (O'Neill 2004).

Laser beam drilling enables processing of small holes with high aspect ratios, high angles of incidence, or with undercuts (Dahotre and Harimkar 2008). It can be an alternative process to mechanical drilling or electric discharge machining (EDM), especially if holes must be formed under difficult conditions (hardened materials, high angles of incidence). The drilling approaches are




**Laser Beam Machining, Fig. 2** Laser cutting techniques: (**a**) fusion cutting, (**b**) oxygen cutting, (**c**) sublimation cutting (cf. Kaplan 2002)



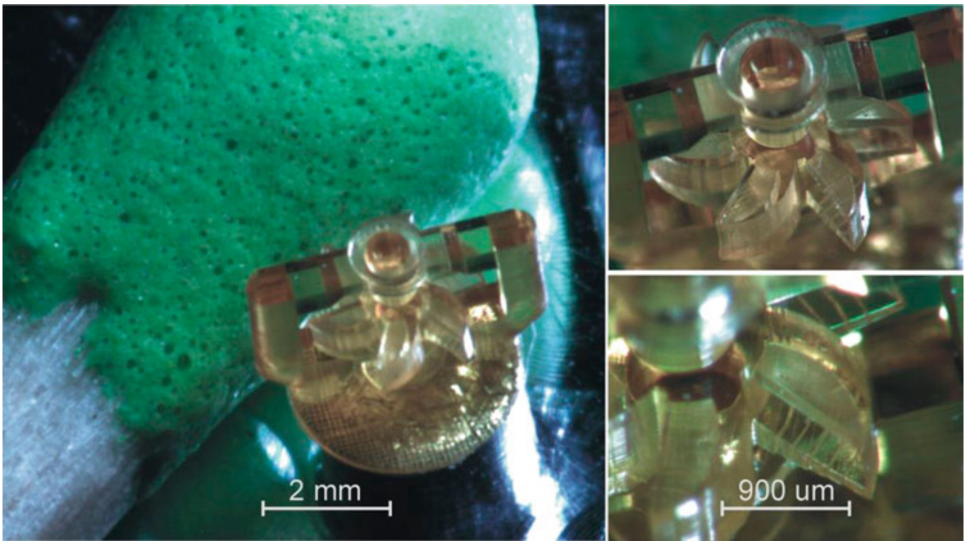

**Laser Beam Machining, Fig. 3** Process approaches for drilling and machining with focused laser beams

**Laser Beam Machining, Table 1** Overview of laser cutting techniques

| Type of Cutting | Materials |
|---|---|
| Fusion cutting | Ceramics; applicable to all metals including stainless and high alloyed steels, aluminum, titanium, and copper alloys |
| Oxygen cutting | Non-alloyed and low-alloyed steels; stainless steels; titanium; aluminum alloys; carbon steels |
| Sublimation cutting | Plastic sheeting and textiles; non-meltable materials: wood, cardboard, foam; diamond; acrylics; thermoplastic polymers; rubbers; paper; leather; thin metal sheets |

**Laser Beam Machining, Table 2** Laser sources used for cutting

| Source | Output power | | Application |
|---|---|---|---|
| Fiber laser | 6 kW | Thick sheets | Stainless steel, mild steel, aluminum up to 20 mm; copper, brass: up to 6 mm |
| $CO_2$ laser | 7 kW | Thick sheets | Stainless steel: 30 mm, mild steel 20 mm, aluminum 20 mm |
| Fiber laser | $>$ 20 W | Thin sheets | Cutting width (different metals/alloys) $< 16$ µm |
| Nd: YAG laser | 7 W | Thin sheets | Cutting width (different metals/alloys) $< 20$ µm |




**Laser Beam Machining, Fig. 4** Micromechanical components with moveable parts generated by laser-based layer manufacturing (microstereolithography)

generally classified into three strategies: single pulse, percussion, and trepanning drilling (Fig. 4a–c). While in single pulse and percussion drilling, the laser pulses are placed on the same spot, in trepanning drilling translation stages, scanners or rotating optics are used to move the laser spot along the circumference of the hole.

With single pulse and percussion drilling, holes with 20 µm–1 mm diameter can be formed. The drilling depth is limited at around 1 mm for single pulses and up to 25 mm for percussion drilling (Dahotre and Harimkar 2008). Nd:YAG laser sources with pulse lengths ranging from ns to µs regime are most commonly used due to their high pulse energy. Typical applications using the percussion drilling are generation of holes in aircraft turbine blades or drilling of microvias in printed circuit boards (PCBs) in electronic industry. Drilling rates up to 250 vias/s with 30 µm via diameters are reported. With the trepanning strategy, holes of less than 3 mm are drilled. By using rotating drilling optics, the laser beam can be rotated with an overlaying wobbling. Tapered nozzle holes with small diameters on the entrance and large diameters on the exit site of the laser beam can be generated in this way, e.g., fuel injection nozzles in steel for gasoline engines.

Besides laser drilling, laser beams are used in a large variety of ablation processes, exemplary: micromachining, thin film patterning, cleaning, scribing, or as a surgical tool. Laser pulses with pulse durations in the nanosecond to femtosecond range are used since the heat affected zone can be reduced and therefore process resolution enhanced (Meijer et al. 2002). This enables high precision machining with resolution down into the sub-µm regime.

In industrial applications, laser machining approaches are generally classified in imaging and writing techniques. The imaging techniques are based on projection of a mask onto the surface of a workpiece. The process resolution of the imaging system is diffraction limited and can be estimated by the equation:

$$\Delta x \approx 0.6 \frac{\lambda}{NA}$$

where $\lambda$ is the wavelength of the laser radiation and $NA$ the numerical aperture of the imaging optics. Laser beam writing is realized by focusing the beam to a small spot and scanning across the surface (cf. Fig. 3d). The spot size is limited to about

$$w_0 \approx \frac{\lambda f}{D}$$

Here, $f$ is the focal length of the focusing lens and $D$ is the beam diameter at the lens entrance face. In order to overcome diffraction limits, techniques of laser nano-machining have been developed (Li et al. 2011). These techniques are based, e.g., on nonlinear laser absorption, laser interference lithography, or near-field processing. However, development of commercial nanoscale applications is still in its beginnings.

### Surface Treatment

Due to its locally well-defined and concentrated energy input, laser radiation is suitable for surface treatment applications of small and complex part geometries with almost no dilation. In contrast to other methods, laser surface treatment is also characterized by high cooling rates. Laser hardening allows the generation of hard and wear-resistive austenitic surface layers on steel and cast iron by heating the target zone to a specific temperature for a specific time period. Since a homogeneous intensity distribution is required, often shaped laser beams are used for hardening. Beam shaping can be done, e.g., with diffractive optical elements or integrator mirrors. Laser remelting is based on the same approach but aims for short-term melting of the target zone material which results in an advantageous microstructure. Using scanner system, a laser beam can be moved over a large target zone in a meander-shaped line causing a local remelting. This results in a smoothed surface since the melt tends to minimize its surface energy. In a second step, the laser polishing process is finalized by removing the remaining surface roughness through laser pulses in the nanosecond range. During laser alloying, in the molten phase, additional material is fed which is completely molten, dissolved, and alloyed with the base material through convection processes. In contrast to laser alloying, the addition material is not or only partly molten in laser dispersing. Both methods aim for modifying the surface layer toward improved wear resistance.

### Layer Manufacturing

During layer manufacturing (or additive manufacturing technologies), laser radiation is used to generate sequences of layers with defined thickness. Through the stepwise production and stacking of individual layers, solid three-dimensional parts can be produced, by only using the geometrical information of each individual layers on the one hand and the layer material on the other hand. The geometrical layer information is provided by three-dimensional, virtually sliced CAD data, while base materials for layer production can be liquid, photo-curable monomers (resins), or metallic, ceramic, and polymer powders. Thin foils or blank sheets are also applied. No additional tools, mold, or masks are required.

From the beginning and still today, layer manufacturing techniques are mainly used for fast and cost-efficient production of prototype parts for concept studies (rapid prototyping). But, since applicable materials and reliable machinery have been developed recently, research and development have been increased to investigate the production of end user parts (direct manufacturing, rapid tooling). The applicability of layer manufacturing for precision engineering has also been shown (Fig. 4).



## Cross-References


- ▶ Additive Manufacturing Technologies
- ▶ Electric Discharge Machining
- ▶ Laser Ablation
- ▶ Laser Welding
- ▶ Pulse
- ▶ Rapid Tooling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## Laser Beam Processing

▶ Laser Beam Machining

## Laser Beam Welding (LBW)

▶ Laser Welding

## Laser Peening

▶ Peening

## Laser Pulse

▶ Pulse

## Laser Welding

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### Synonyms

Laser beam welding (LBW)

### Definition

Laser welding is a collective term for fusion welding using a coherent beam of monochromatic light as the heat source. Welds may be fabricated with or without filler material and with or without shielding gas (Geiger et al. 1998). Laser welding is applied to weld commercially important metals, including steel, stainless steel, aluminum, titanium, nickel, copper, and certain dissimilar metal combinations. Also polymers and some ceramics can be laser welded.

### Theory and Application

#### Overview

The term LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. A medium, either gaseous or solid, is excited to emit a monochromatic (single wavelength) and coherent radiation. This radiation can be focused via optical systems to a point at the workpiece, called spot. It results in a high-power density (irradiance), capable of vaporizing various materials. The welding effect is achieved by controlling the power density applied to the materials. Both the laser power and the focused spot size are crucial parameters. Depending on the welding requirements, the assistance of gases and filler materials can be necessary. The laser type for *welding* is selected according to the application: an infrared wavelength for large-scale applications or a shorter wavelength for *microprocessing*. The laser beam is formed into a geometry that is appropriate for the application and the area to be welded by a suitable optical head. Several parameters resulting from the welding setup characterize the laser welding process. The beam parameter product (BPP) is the product of a laser beams divergence angle Θ and the diameter of the beam at its narrowest point (the beam waist) divided by four (ISO 11146-1 2005). It quantifies the quality of a laser beam and how well it can be focused to a small spot on the workpieces. Therefore, it is an important optical parameter affecting the welding process.

$$BPP = \frac{d_f \cdot \theta}{4} \; in\ mm{\cdot}mrad \tag{1}$$

The power per unit area of electromagnetic radiation at the workpiece surface is defined by the irradiance *I*. Its specific value, depending on the combination of laser, materials of the workpieces, and gas, characterizes surface heating, melting, heat conduction mode welding, and deep penetration welding. The SI unit for the irradiance is watts per square meter (Hecht 2005).

$$I = \frac{dP}{dA} \quad in \quad \frac{W}{m^2} \tag{2}$$

The aspect ratio V of a seam is the ratio of its longer dimension to its shorter dimension in its cross section. It specifies whether heat conduction mode welding or deep penetration welding was executed (Poprawe 2005).

$$V = \frac{h}{b} \tag{3}$$

## Theory

### Heating and Surface Melting

The energy input into the substrate is low in comparison with a conventional means of welding, causing little residual stress. Beside that the heating rates associated with laser melting are orders higher than for conventional methods. Melting therefore occurs rapidly, with an associated increase in the absorptivity of the material to the laser beam (Ion 2005). This characteristic behavior is depicted by a typical diagram presenting the dependence of the welding depth to the applied irradiance (Fig. 1). The diagram is also used to determine the threshold separating the heat conduction mode welding from the deep penetration welding.

### Welding Modes

**Heat Conduction Mode Welding** Heat conduction mode welding describes a family of effects in which the laser beam is adjusted to give a power irradiance of $I \approx 1{\cdot}10^8 \frac{W}{m^2}$ which is used to create a joint without significant vaporization during welding. The process displays no interaction between the incident laser beam and the hot vapor, because the vapor density is below its threshold (Cremers and Radziemski 2006). As Figure 1 describes, heat conduction mode welding produces low welding depths ($I \leq 1{\cdot}10^{10} \frac{W}{m^2}$ for steel) at low irradiance levels. During this process, an increase of irradiance below the threshold results only in a small increase of penetration depth and a low aspect ratio. This is often required when limited penetration in the workpieces is desired. The welding mechanism involves absorption of the beam energy by the material surface (*Fresnel absorption*) and a subsequent transfer of energy into the surrounding material by heat conduction.

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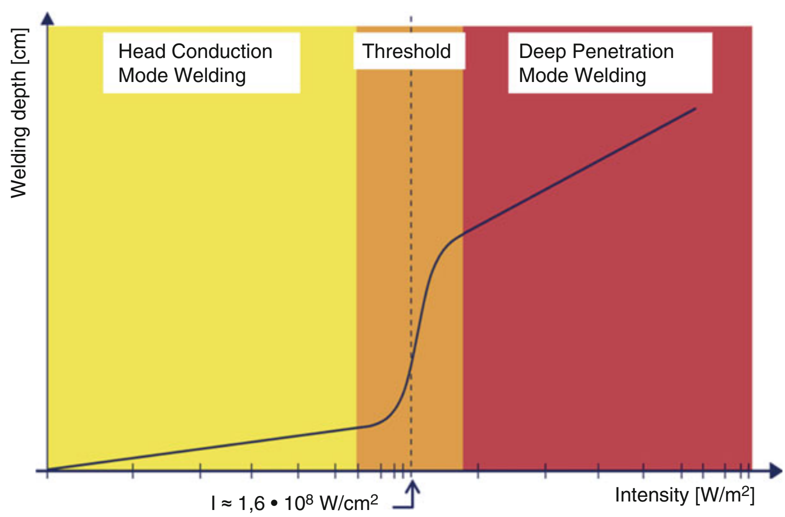



**Laser Welding, Fig. 1** Characteristical welding behavior depicted by a schematic diagram presenting the dependence of the welding depth to the applied irradiance

A hemispherical weld bead and heat-affected zone (HAZ) is formed in a similar manner to conventional arc fusion welding processes. Provided that fusion of all components can be achieved (e.g., the fusion of alumina at aluminum surfaces cannot be achieved), the properties of the weldable materials are relatively unimportant (Ion 2005). Only in metals under reducing atmosphere (e.g., $CO_2$) or special solute concentration (e.g., sulfur in steel) the so-called Marangoni effect can occur resulting in a deeper penetration (Zaeh et al. 2009). Most conduction laser welding configurations employ a high-power diode laser (HPDL) or a defocused beam of a more brilliant laser, e.g., an Nd:YAG laser. Therefore, this welding process does not need to have a high beam quality.

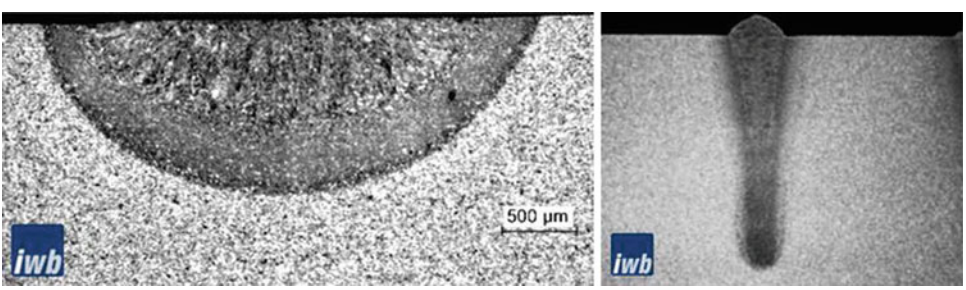
**Deep Penetration Mode Welding** In deep penetration mode welding (also called keyhole welding), the beam is focused to its smallest spot size, resulting in an incident irradiance at the workpiece surface beyond $> 1 \cdot 10^{10}$ W/m$^2$. At this irradiance, a significant amount of hot vapor can be generated, which interacts with the incident laser beam. As a result, the fusion surface continues to deform by the recoil force of vaporization until a vapor-filled capillary (keyhole) is generated. The diameter of the keyhole is typically in the range of the beam diameter. The vapor capillary is surrounded by the liquid phase of the material during the whole welding process (Hügel and Dausinger 2004). As shown in Fig. 1, the deep penetration area is distinguished from the heat conduction mode welding area by a range containing the threshold irradiance. At the threshold irradiance, an erratic increase of penetration depth labels the beginning of the deep penetration welding. The threshold itself can be influenced by irregularities at the workpiece surface. For example, rust stains at steel absorb in the infrared better than the blank steel surface. Such irregularities can initiate the deep penetration welding. During initiating the keyhole, absorptivity increases drastically because of multireflections at the keyhole walls. Therefore, an increase of Fresnel absorption (Hügel and Dausinger 2004) also occurs. The keyhole is maintained by equilibrium between the forces created by the vapor pressure and those exerted by the surrounding molten material. In fully penetrating welds, the molten zone and the heat affected zone are narrow and deep (Fig. 2).

The deep penetration welding can be defined by the following significant criteria (Steen 2003; Poprawe 2005):

- Aspect ratio < 3–4
- Nearly straight dendrites toward the center line of the seam
- Acoustical emission, because of the compressional waves
- High hot vapor density above keyhole
- Increased absorption because of multireflections at keyhole walls

### Cooling and Solidification

Temperature gradients within the melt pool control cooling rates and when combined with solute gradients influence solidification microstructures. With relatively low cooling and




**Laser Welding, Fig. 2** (*Left*) cross section of a heat conduction mode welded seam; (*right*) cross section of a deep penetration welded seam solidification rates, primary solidification products may be estimated from equilibrium phase diagrams and charts such as the *Schaeffler diagram* for high-alloyed steel species or the *carbon equivalent* for low-alloyed species (Dilthey 2005). Planar, cellular, dendritic, or eutectic solidification fronts may form, depending on the temperature gradient, the rate of solidification, and solute concentration gradients. Dendrites form with temperature gradients, and solidification rates are therefore typical for laser welding applications.

The produced integrity of seams by laser welding is high. The melted region exhibits low porosity and few imperfections and has a sound metallurgical bond with the substrate (Fig. 2).

### Applications

The market for industrial laser systems is very mature and has been growing steadily for almost 30 years. In 1979, the first two-dimensional laser-cutting systems were introduced as tools for the fabrication industry. Today, this market has expanded from cutting to welding and from two- to three-dimensional applications (Krastel et al. 2006).

For years, typical applications of diode lasers and therefore heat conduction welding are battery boxes, rubber gaiters, or high-quality steel sinks. Furthermore, diode lasers are suited for spot welding of electronic components.

A major part of laser welding is in the automobile industry where the welding of the roof body shell with the side frame was one of the first applications. Modern remote laser welding systems enable new welding applications because of drastically improved productivity and speed. In recent years, stationary systems based on $CO_2$ lasers and robot-controlled systems using solid-state lasers have been introduced into the industrial marketplace. Remote laser welding is the latest in a series of successful industrial laser solutions that have revolutionized sheet metal processing over the past 30 years.

## Cross-References

▶ Welding

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## Laser-Assisted Cutting

▶ Hybrid Cutting

## Laser-Assisted Machining

▶ Hybrid Cutting

## Laser-Assisted Milling

▶ Hybrid Cutting

## Laser-Assisted Turning

▶ Hybrid Cutting

## Lathe

▶ Machine Tool

## Layout Planning

▶ Facility Planning

## LCA

▶ Life Cycle Assessment

## Lean Design

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### Synonyms

Lean engineering design; Lean development

### Definitions

Lean design is a term increasingly being used by both academics and practitioners to refer to lean principles applied in the context of design. However, as this context is not uniform, the meaning of lean design is not either. Lean design can be used as a *synonym of lean development* (which refers to leaning the processes required to be undertaken for translating a market need into a manufacturable device, as it is used in Ward and Sobek (2014), Ōno (1988), and Bauch (2004)), *as a verb* (referring to having the process of designing being performed in a lean fashion, as it is used by Baines et al. (2006)), and *as a noun* (referring to an object that fulfills a set of desired functions by being lean, as it is used in Johansson and Sundin (2014), Dombrowski et al. (2014), and Gautam and Singh (2008)). All three definitions are intrinsically founded upon the principles of the lean philosophy: eliminating non-value-adding activities (for a process) or sub-functions (i.e., subpart or components for a product) relatively to the needs of the end customer. From the perspective of the consumer of the product or service, the value refers to the expected functionalities of the product or process, according to the amount the customer is willing to pay for. Lean approach preserves value with less work or resources involvement. Based on this, the following definitions can be drawn:

**Definition 1**: Lean Product Design (*synonym of Lean Product Development*). Is a product development process characterized by reacting to information continually as it is being generated, keeping product options open longer and enabling the engineers' continuous (re)action on new information about customers, markets, suppliers, and production capabilities. Lean product development, as described by Morgan and Liker (Ward and Sobek 2014), refers to the management of (1) skilled people, (2) tools and technologies, and (3) information and decision-making during the phases of product development process (e.g., problem analysis, concept design, layout design, detail design, testing and prototyping, and finally, production ramp-up as described by Ulrich (Ulrich et al. 2011)).

**Definition 2**: Lean Design (*verb*). Is a design process that focuses on continuous customer value maximization while minimizing all activities and tasks that are not adding value. Lean design deals with a subset of methods and tools of lean product development, targeting the conceptual, layout, and detail design phases.

**Definition 3**: Lean Design (noun). Lean design can be seen as minimal (lean) functions that fit to the customer's needs, maximizing added value with minimizing materials, energy, and overfunctionalities.

The difference in meaning of lean design according to its grammatical form (noun vs. verb) is a direct result of the grammatical forms of the term design. In fact, for both the noun and the verb definition of lean design, an adjective (for the first case) and adverb (for the second) provide a more specific meaning of the term design.

## Theory and Applications

Lean philosophy originates at the Toyota Production System (initiated by S. Toyoda) in the 1970s. The lean thinking (Womack and Jones 2003) approach initially started for manufacturing and mixing just-in-time tools and Jikoda methods. Companies applying lean principles have a deep understanding of customer value and concentrate its main processes for constant improvement of it. Moreover, the aim of the company is to deliver, to the consumer, the perfect value obtained by the perfect, wasteless process (Jones and Roos 2009). To be able to achieve this goal, thinking in the lean way switches the management attention from single processes, technologies, departments, etc. to product flow through complete value streams (Jones and Roos 2009). The value stream should be as big as possible, which is obtained by setting one by one the steps that add value to the next ones and removing the non-value-adding steps. A significant help here can be received from the visual management, which will support employees and management to instantly see where the process differs from the perfect one and what is working and what is not.

Lean thinking is an "improvement philosophy which focuses on the creation of value and the elimination of waste." Its first focus was on manufacturing, based on the good practices of Japanese automotive industry since post Second World War. Later in the 1990s, tools and methods have been created to support and to spread lean manufacturing to other industries. Lean is not restricted to one single method but to a family of tools and methods. It is now applied as a strategic and management method and can be applied to many systems. However, the definition of lean is drifting. While earlier papers saw lean as a philosophy for waste reduction, the emerging view is one of value creation (Baines et al. 2006). Lean product design and lean products are more recent applications of lean. The analogy between lean attributes in manufacturing and in product development can be found at Baines et al. (2006). Manufacturing has material flow, and product development has information flow. Lean philosophy focuses on three elements: value, knowledge, and improvement.

The improvements expected from a lean product and process development methods are energy, time and resources reduction (for the product or the design process), quality improvement, and innovation increase (Ward and Sobek 2014). As the results of lean product design are in line with resources optimization, comparisons can be made to green product development, as shown in Johansson and Sundin (2014). The authors conclude that lean product development does not ensure green product and that green products do not insure product development process efficiency, but there are potential cross-field learning between fields.

### The Lean Product Development (LPD) Approach

As in manufacturing, LPD has the goal of eliminating waste such that value can be maximized. However, as the nature of product design processes is intrinsically different than that of manufacturing ones, the concepts of value have their own particular meaning within the LPD approach. As a consequence, the leaning principles are different than in manufacturing too. According to lean design, the design process results in two different types of value: manufacturing systems and usable knowledge. When these values are created in an efficient and effective manner, profitable operational streams emerge (Ward and Sobek 2014).

LPD deals with how these activities are organized in time and distributed among different disciplines and people. In this context, LPD is an operations management method (Karlsson and Åhlström 1996). Some of the most common high-level concepts associated with lean product development are:

1. Creation of Reusable Knowledge. As the goal of lean is to maximize value adding by optimizing knowledge translation into operational streams, reusability of knowledge increases both the effectiveness and efficiency.
2. Teams of Responsible Experts. Lean product development organizations develop integrated work teams with multiple competences in each team and reward competence building in teams and individuals.
3. Cadence and Pull. Managers of lean development organizations reject the scientific management notion that managers plan, and workers do. Rather, engineers plan their own work and work their own plans.
4. Visual Management. Visualization is a main enabler of management in lean product development.
5. Entrepreneurial System Designer (ESD). The lean development organization makes one person responsible for the engineering and aesthetic design, and market and business success, of the product.

## The Lean Design Approach (Verb)

In LPD, effectiveness and efficiency are achieved by the continuous application of two base principles, namely, just-in-time decision-making (JIT-DM) (as described in Holman et al. (2003)) and set-based concurrent engineering (SBCE) (as described in Raudberget (2010)).

JIT-DM consists on taking decisions proactively by acting on the level of information readiness of a given design phase. JIT-DM rests on the base idea that information processing entities (i.e., engineers) can act the most effectively when the information batches required for carrying out those decisions are fully available. Consequently, efficiency also increases, as the decisions made are more effective, and no time is wasted on readapting afore made erroneous ones.

During the SBCE, designers reason about, develop, and communicate sets of feasible solutions concurrently and with certain independence. Then, as the design process proceeds, solutions are evaluated and dismissed based on additional information coming from different disciplines – for example, simulations and tests from the technical departments and consumer needs from the marketing department.

The most well-known and successful industrial implementation of lean design is done at Toyota automobile company, described in Sobek et al. (1999). Here, designers apply set-based concurrent engineering to generate and evaluate sets of solutions. Then, as the design process progresses, implicit knowledge and new coming constraints are used to narrow the solution space. The application of this principle implies that several options are worked out simultaneously, having the final design selection toward the end of the whole product design process. This encourages just-in-time decision-making.

## Approach for Lean Design (Noun)

Lean design as a noun refers to lean product design, in a perspective of eco-design of products and lean function selection or just expected functions and services. Lean design started from the basic idea of lean thinking and focuses on value-adding activities from the perspective of the end customer use. Lean design can be seen as minimal (lean) functions that fit to the customer's needs, maximizing added value with minimizing materials, energy, and overfunctionalities. Lean designed products are mostly driven by cost reduction objective. They can arrive to strategic change such as the switch to product to service. Lean design means lean product and sustainable product.

In order to achieve a product that is lean in its expected function specification, value analysis approaches and value stream serve as important tools. From the design science, the functional analysis (Kaufman 1977) and value analysis (Standard (SAVE International, The Value Society 2007) (or value stream) methods help in defining the minimal functions to be delivered. It should be coupled with the establishment of the customer-defined value to separate value added from waste. The use of life cycle assesment, and life cycle costing approaches, for the designed product, can give the evaluation (at least material, energy, and costs) of the non-value-added save by the leaned designed product. In this sense, Naveen Gautam refers to customer perception on the value of the product and does not only focus on functional answers and minimal function selection to meet the needs.

According to Dombrowski (Dombrowski et al. 2014), the product has different vies:

1. Design View: The product is the sum of parts, their properties, and their relationships.
2. Value View: The product is the sum of functions it performs or properties it offers to create customer value.
3. Waste View: The product is the sum of all life cycle processes.

Lean product design refers mainly to the second point. A well-known example of a design that is lean is the Logan model of Renault (from Renault–Dacia) launched in 2004 and Design from 1999 to 2003, as it has a very restrictive cost objective. The limited set of functions available and the technical solution allow the car manufacturer to propose a cheap and affordable car that meets a huge commercial success.

## Cross-References

► Conceptual Design
► Decision-Making
► Design Methodology
► Design Methodology
► Productivity

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# Lean Development

► Lean Design

## Lean Engineering Design

► Lean Design

## Lean Management

► Lean Production

## Lean Manufacturing

► Lean Production

## Lean Production

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### Synonyms

Kaizen and continuous improvement; Lean management; Lean manufacturing; Toyota Production System; World class manufacturing

### Definition

The term "lean production" was first introduced in "The machine that changed the world," published in 1990 (Holweg 2007), to differentiate Toyota's production practices from mass production in the automotive industry. Thus, lean production can be seen as a synonym to the Toyota Production System (TPS), which is elaborated in this entry. John Krafcik described TPS as a production which "uses less of everything compared with mass production – half the human effort in the factory, half the manufacturing space, half the investment in tools, half the engineering hours to develop a product in half the time. Also, it requires keeping far less than half the needed inventory on site, results in many fewer defects and produces a greater and ever growing variety of products" (Womack et al. 1990, p. ~11). However, lean production is more than a production practice. It is a holistic mindset and management system, contrary to the traditional approach of mass production (Womack et al. 1990).

### Theory and Application

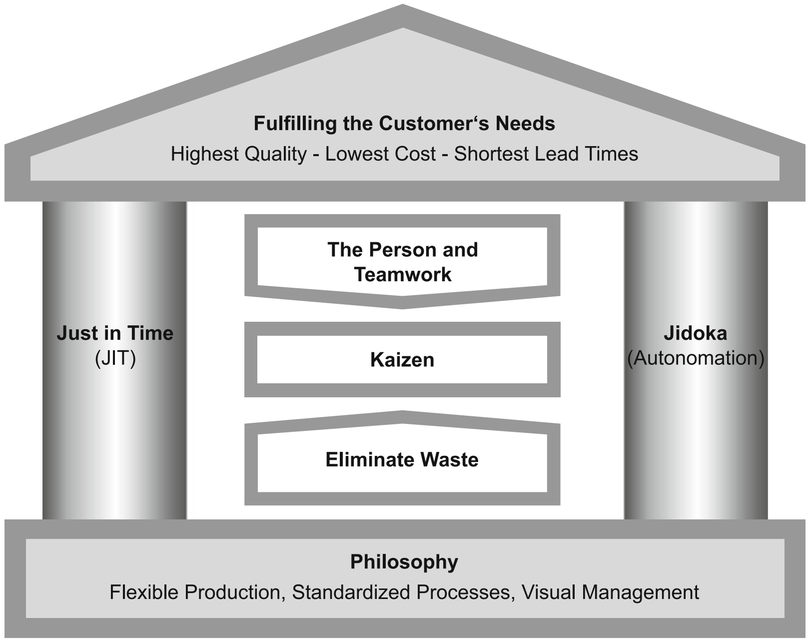
#### The Toyota Production System

##### Origins

Toyota developed its TPS after World War II to cope with capital constraints and low production volumes. TPS was implemented by adapting mass production strategies of American car manufactures to Toyota's situation (Ōno 1988; Holweg 2007). Developed between the late 1940s and 1960s (Ōno 1988), the concept of TPS was first published in English in 1977 (Holweg 2007). Although some TPS-specific tools like Just-in-Time or Kanban had been implemented in western companies in the 1980s, it took more than a decade until TPS became popular in the automotive industry. Published in 1990, "The machine that changed the world" was not only a mere description of Toyota's manufacturing in comparison to European and American car manufactures but a wake-up call for the western industry (Holweg 2007). In the subsequent years, many companies were implementing TPS more or less successful. These companies only applied single methods and without regarding the basic principles.

##### Principle

The overall objective of the TPS, depicted in Fig. 1, is to only provide products that fulfill the customer's needs. According to Ōno (1988, p. ix), founder of TPS, the underlying principle of the TPS can be summarized as follows:




**Lean Production, Fig. 1** Toyota Production System (Ōno 1988)

> All we are doing is looking at the time line [. . .] from the moment the customer gives us an order to the point when we collect the cash. And we are reducing that time line by removing the non-value-added wastes.

As mentioned before, fulfilling the customer's needs is the overall objective of TPS. In order to reach this objective, products need to be manufactured at the highest quality, with the lowest cost and shortest lead time. To achieve these derived goals, the system of TPS requires two primary pillars Just-in-Time (JIT) and Jidoka (Autonomation) (Ōno 1988).

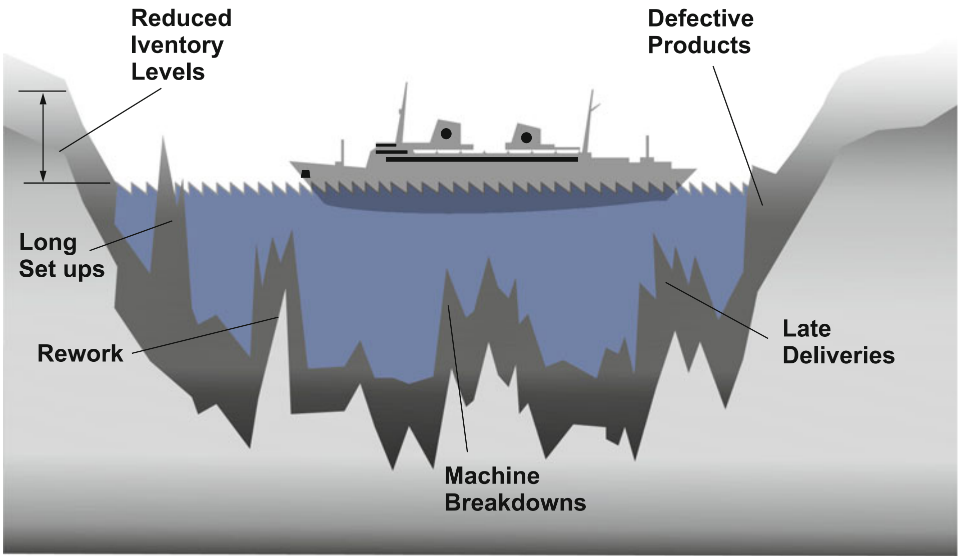
The concept of *JIT* is to produce and deliver the right parts, in the right quantity, at the right time using a minimum of resources. Thus, the inventory level can be reduced and, additionally, an overproduction is avoided. However, a reduced inventory level bears the risk that the process is more susceptible to disturbances, e.g., concerning long set ups, rework, machine breakdowns, late deliveries or defective products, and can result in a standstill of production (Takeda 2006). This condition can be analogously pictured by a ship on the water (cf. Fig. 2). The water level symbolizes the inventory level. The ship can sail as long as the water level is high enough to cover the reefs. However, the lower the water level gets, the higher the probability that the ship might run aground on various reefs, presenting the abovementioned disturbances. By reducing the inventory level, these hidden obstacles become visible and need to be eliminated.

*Autonomation* focuses on two major aspects including (1) integration of quality assurance measures in the production process and (2) separation of man and machine in the production environment. Processes should be designed such that they are capable to switch off automatically if a deviation of a regular condition, e.g., problems or defects occur (Ōno 1988).

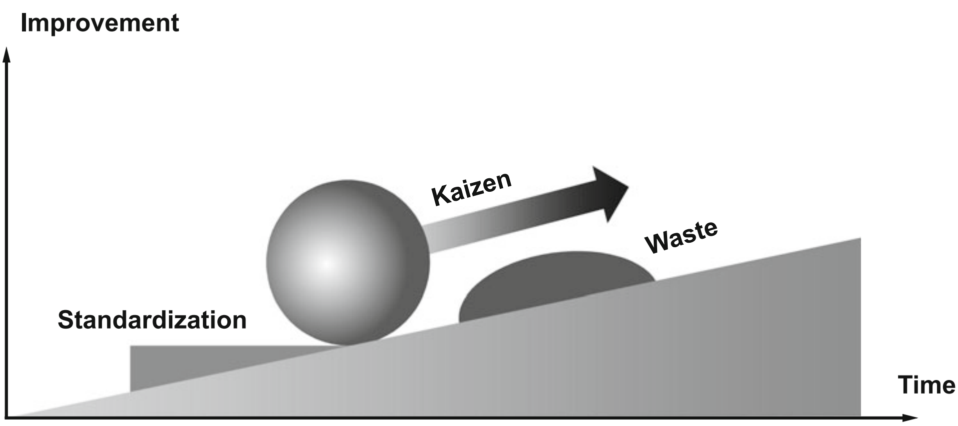
The TPS is not only focusing on the production process itself: One of the most successful factor of TPS is striving for continuous improvement (Jap. Kaizen) over time by eliminating waste through mutual participation of all employees. This context is also shown in detail in Fig. 3.

Waste, also referred to as "muda," has different characteristics that are summarized in Fig. 4 (Ōno 1988).

These wastes are briefly described in the following:




**Lean Production, Fig. 2** Link between inventory level and disturbances (Takeda 2006)

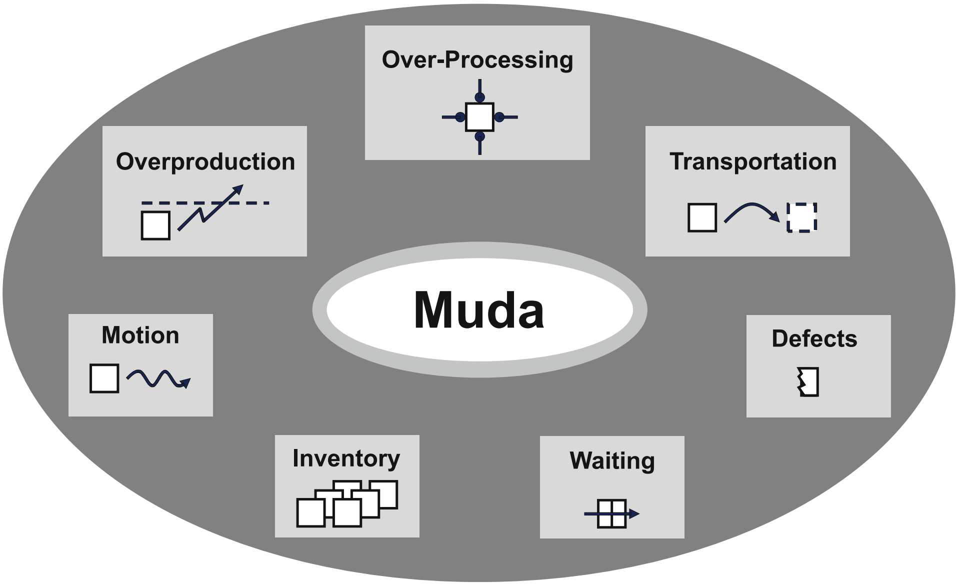



**Lean Production, Fig. 3** Striving for continuous improvement (Kaizen) over time by eliminating waste and implementing standards

- *Over-processing* reveals that more time or effort is spent for a production task than necessary.
- *Transportation* indicates nonessential movements of a products, e.g., due to inefficient layouts.
- *Defects* in products are a result of poor internal quality and cause rework or scrap.
- *Waiting* stems from, e.g., machine breakdowns, long set ups or late deliveries.
- *Inventory* contributes to long lead times and prohibits a smooth, continuous workflow.
- *Motion* denotes unnecessary movements of a worker that amount to time and energy.
- *Overproduction* is a result of producing too much and producing too early.

By eliminating waste in the production process, costs and lead time can be reduced.

According to Ōno (1988), there exist further types of impairment that affect the production process. These interferences are “muri” (Engl. overload) and “mura” (Engl. uneven production), while the latter is a result from a process shifting




**Lean Production, Fig. 4** Seven kinds of waste (muda) (Ōno 1988)

continuously between waste ("muda") and overload ("muri").

Another step to reach the overall objective is the integration of all employees to solve occurring problems or interferences efficiently. Both, the elimination of waste and the integration of each employee, contribute toward the principles of Kaizen to improve the production process in terms of time, cost, and quality.

The foundation of the TPS is to implement a flexible production depending on the market demand, standardized processes to ensure a constantly high level of quality and a visual management to identify and eliminate problems and waste more quickly. This basis is stabilized by the underlying philosophy of the TPS to reduce cost by continuous improvement and eliminating wastes.

## Methods

In order to implement the two pillars of the TPS (Ōno 1988), JIT and Autonomation, various methods were developed. To apply a method effectively, particular prerequisites need to be fulfilled. Besides, each method has advantages and disadvantages regarding its application and therefore the suitability of each method has to be ascertained beforehand. In the following, popular methods are assigned to the two pillars and briefly described:

Methods that contribute to the concept of *JIT*:

- *Value Stream Mapping (VSM)* is a method for analyzing production and design flows. Since it focuses on the customer, it helps to identify waste ("muda") and bottlenecks and to outline a smooth production flow (Rother and Shook 1999). VSM is a common method to start Kaizen activities because it enables the analysis of the whole processes and concatenates different lean concepts and techniques.
- *Value Stream Design (VSD)* is the subsequent method of VSM to plan ("design") a future-state map of a production or design process. It provides ten design guidelines to achieve lean processes including different principles and methods of lean production (Erlach 2012).
- *Kanban* is the most common method of lean production and is often misleadingly equated with it. Kanban is the Japanese word for card and defines the practical implementation of the pull principle by using rotating cards between

source and sink of material to organize the production supply. The main effect is the stabilization of the inventory stock level (Ōno 1988). However, a Kanban system would never run without inventory since a so-called supermarket has at least to be filled with inventory to bridge the replenishment time.

- *Single Minute Exchange of Die (SMED)* is a method of reducing lot sizes to achieve lower inventory stock levels by reducing the change-over time. Primarily designed for the application in body press shops by Shigeo Shingo, SMED had been established as a universal method to optimize technical setup operations (Shingo 1985).

Methods that contribute to the concept of *Autonomation*:

- *5S* (or Five S's) is a method of five steps to create a workplace for lean production and visual control. The name of the method is based on the terms for the five steps *seiri (systematic arrangement)*, *seiton (sort)*, *seiso (shine)*, *seiketsu (standardize)*, and *shitsuke (sustain)*. 5S is usually the first step in the implementation of lean production because it helps to form standards as a basis for continuous improvement (Womack and Jones 1996).
- *Poka Yoke* is Japanese and can be translated as "mistake-proofing" (Shingo 1988). It is a mechanism that helps operators avoiding mistakes and is effective for correcting quality defects. Solutions are designed to avoid or detect mistakes directly to achieve a zero defect production.
- *Heijunka* focuses on reducing an unevenness in production ("mura") by decoupling the production program from the customer's orders. It is characterized by a repetitive production pattern which smoothes the day-to-day variations to correspond to the long-term demand (Womack and Jones 1996).
- *Total Productive Maintenance* (TPM) is not an element of the Toyota Production System, but it is often set in context with lean production. The term includes different maintenance activities and strategies to improve the equipment effectiveness sustainably. One important element is the involvement of operators in routine maintenance (Wireman 2004). While TPS focuses on zero defect production, TPM targets on zero machine breakdowns, so both concepts supplement each other.
- *Chaku-Chaku* denotes a principle for synchronized cell manufacturing to react quickly to fluctuating customer demands. It is based on low-cost automation realized by simple automatic machines that are linked and mostly arranged in a U-Layout to produce specific products in a one piece flow. The quality assurance is integrated in the process. The employees, working in the Chaku-Chaku-Line, mainly focus on the loading and activation of the machines (Yagyu 2007).

### Toyota Management

Toyota's success is based on two essential elements: the management thinking and routines. The management routines are known as kata, which is the Japanese word for routine (Rother and Shook 1999). Rother and Shook (1999) differ between two fundamental ways of kata: The improvement kata which is the routine for all Kaizen measures and the coaching kata that is the routine for teaching the first one within the organization.

The *improvement* kata consists of a fixed vision and a target condition. The target condition is an achievable state in the direction of the vision and helps to identify obstacles on the way. This helps to derive concrete measures to overcome those obstacles. By eliminating existing obstacles, the target condition is reached. Consequently, a new, more challenging target condition can be set. Therefore, the current condition is moving continuously toward the vision (Rother and Shook 1999).

The *coaching* kata is about leadership. In contrast to typical leadership, Toyota leadership is much more interactive than the classical setting of goals downstream and reporting results upstream. Each manager serves as a mentor for his subordinates, while both of them have an overlap of responsibility. The mentee is responsible for the task itself, while the mentor is responsible for the results. Thus, the mentor is much more involved in the mentee's improvement kata process. Within rapid cycles, the manager and his subordinate are solving one obstacle at a time by leading with questions (Rother and Shook 1999). This method helps the mentee to solve the problem by himself. One peculiarity of leading with questions is the 5W (or 5 Why) method to identify the root cause of a problem by asking "why" five times (Womack and Jones 1996).

## Cross-References

- ▶ Lean Design
- ▶ Manufacturing
- ▶ Optimization in Manufacturing Systems, Fundamentals
- ▶ Production

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# Learning Factory


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## Definition

Various definitions of the term "Learning Factory" were proposed and intensively discussed within the community (see, e.g., Initiative on European Learning Factories 2012; Wagner et al. 2012; Tisch et al. 2013; Kreimeier et al. 2014). Within a corresponding CIRP Collaborative Working Group (CWG), an agreement on the following definition could be achieved:

> A Learning Factory in a narrow sense is a learning environment specified by
>
> - **processes** that are *authentic*, *include multiple stations*, and comprise *technical* as well as *organizational* aspects,
> - a **setting** that is *changeable* and resembles a *real value chain*,
> - a *physical* **product** being manufactured, and
> - a **didactical concept** that comprises *formal, informal and non-formal learning*, enabled by *own actions of the trainees* in an *on-site learning* approach.
>
> Depending on the **purpose** of the Learning Factory, learning takes place through *teaching*, *training* and/or *research*. Consequently, learning outcomes may be *competency development* and/or *innovation*. An operating model ensuring the sustained operation of the Learning Factory is desirable.
>
> In a broader sense, learning environments meeting the definition above but with
>
> - a setting that resembles a *virtual* instead of a *physical value chain*, or
> - a *service* product instead of a *physical* product, or
> - a didactical concept based on *remote learning* instead of *on-site learning*
>
> can also be considered as Learning Factories.

Figures 1 and 2 visualize the definition.

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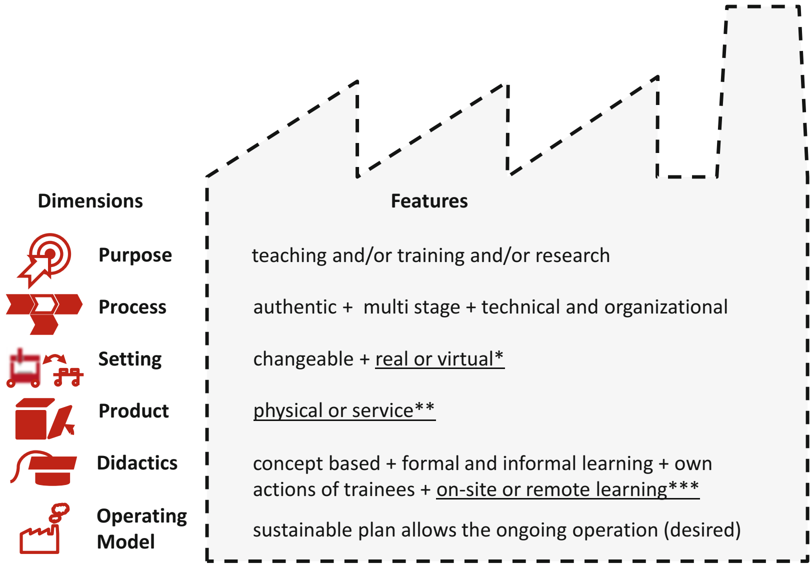
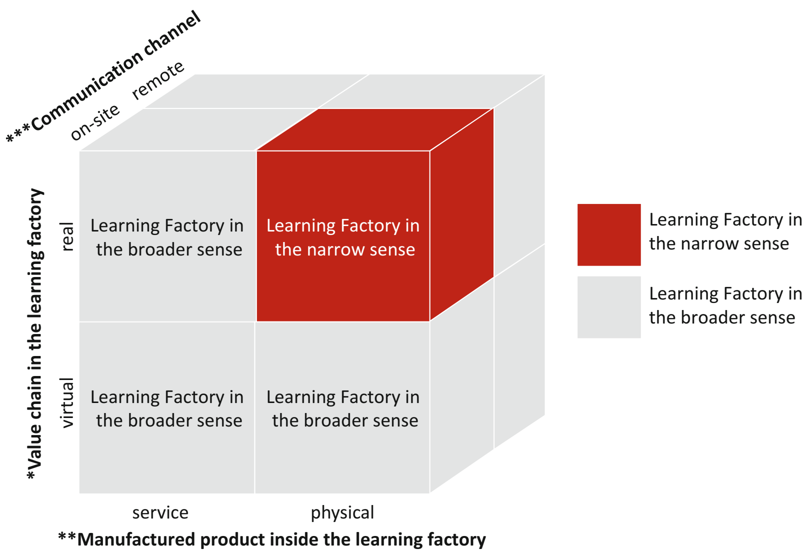



**Learning Factory, Fig. 1** Key characteristics of Learning Factories (Abele et al. 2015)




**Learning Factory, Fig. 2** Learning Factories in the narrow and in the broader sense (Abele et al. 2015)

## Theory and Application

Manufacturing education as a major driver for excellence in manufacturing (ManuFuture 2006) will be challenged significantly in the future (Chryssolouris and Mourtzis 2008): megatrends with strong effects on manufacturing – like declining product lifecycles, a rising number of product variants, globalization, or an increased frequency of job rotation (Abele and Reinhart 2011) – require a shift towards lifelong learning and increased competency building in manufacturing. In order to support this shift and to ensure the sustained growth of the manufacturing industry, both educational content and its didactical approaches need to be adapted to the new situation (Chryssolouris et al. 2013). "Learning Factories" present a promising approach.

The first "Learning Factories" were jointly founded in 1994 at Pennsylvania State University, the University of Washington, and the University of Puerto Rico-Mayaguez under a shared financial program. The leading goal was to supplement the rather theoretical engineering studies with practical, hands-on manufacturing experience as well as communications and teamwork skills (Jorgensen et al. 1995; Lamancusa et al. 1997; Lamancusa and Simpson 2004). Independently from these first initiatives, towards the end of the first decade of the new millennium, several other Learning Factories were established, mainly in Europe. These new Learning Factories greatly vary in size and core topics (Abele et al. 2015; Wagner et al. 2012) and are operated by both academic and private organizations like industrial and consulting companies.

While the initial setups of Learning Factories were started isolated from each other, the networking and collaboration between the individual Factories grew in the following years. Next to informal networking, milestones for formal collaboration were as follows:

- The establishment of the yearly "Conference on Learning Factories" in 2011
- The establishment of the "European Initiative on Learning Factories" in 2011
- The establishment of the CIRP Collaborative Working Group (CWG) "Learning Factories for future oriented research and education in manufacturing" in 2014

Besides the increased collaboration, this new generation of Learning Factories follows a goal-oriented, strategic, and scientific approach for enhancing the learning in Learning Factories (Abele et al. 2015). Beyond, Learning Factories were more and more leveraged also for research.

## Theory

While the first Learning Factories were installed in a hands-on approach with the mindset of a "good engineer," recent research has put scientific knowledge and methodology to the setup and further development of Learning Factories. Current research topics are as follows:

- Establishing an overview on different types of Learning Factories in a morphology and in typologies (see, e.g., Abele et al. 2015; Wagner et al. 2012; Tisch et al. 2013; Steffen et al. 2013, see Fig. 3)
- Strategic setup of a Learning Factory curriculum and environment (see, e.g., Tisch et al. 2013; Riffelmacher 2013)
- Measurement of learning success in Learning Factories (see, e.g., Cachay et al. 2012; Tisch et al. 2014)
- Potentials and limits of learning and research in Learning Factories

For 2017, a CIRP keynote paper on "Learning Factories" is planned, comprising the global state of the art.

As the main platform for the scientific exchange on Learning Factories, the "Conference on Learning Factories" plays an important role. So far, the conference was held in the following:

- Darmstadt, Germany, 2011 (Abele et al. 2011)
- Vienna, Austria, 2012 (Sihn and Jäger 2012)
- Munich, Germany, 2013 (Reinhart et al. 2013)
- Stockholm, Sweden, 2014
- Bochum, Germany, 2015
- Gjøvik, Norway, 2016 (plan)
- Darmstadt, Germany, 2017 (plan)

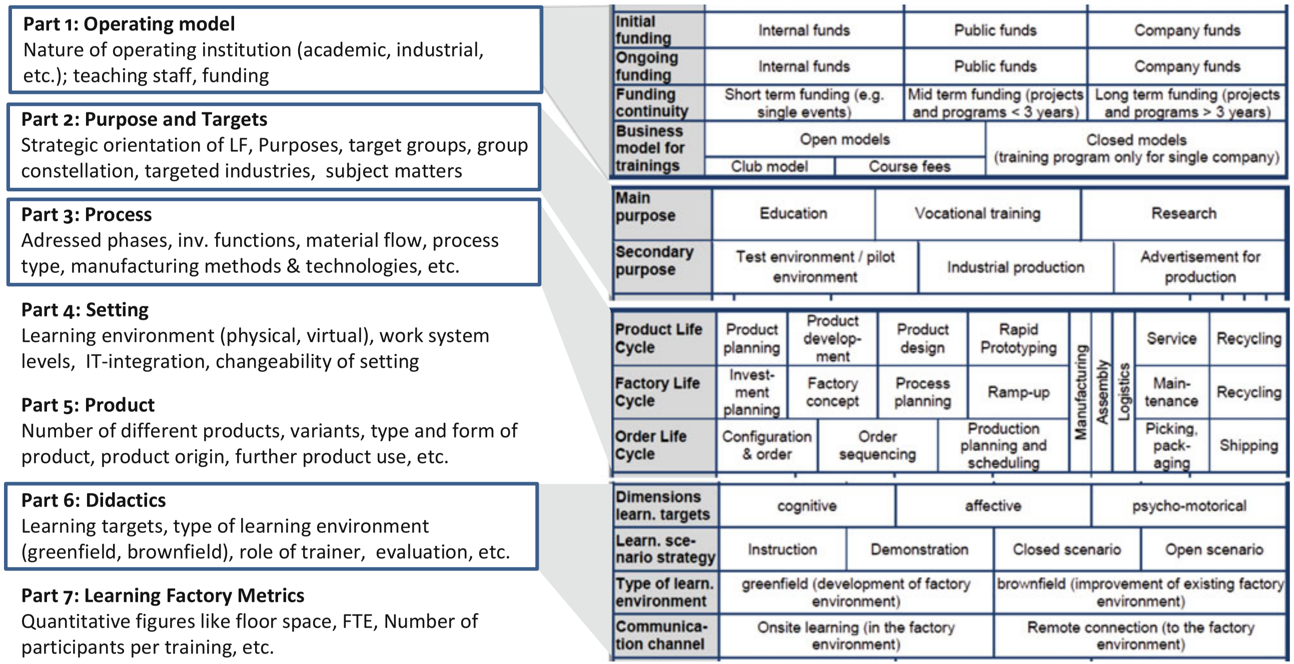
## Application

A multitude of industries operates Learning Factories:

- Educational institutions
- Automotive
- Consulting
- Machine building industry
- Process industry

The topics dealt with in Learning Factories comprise

- Productivity improvement/industrial engineering/lean manufacturing
- Energy efficiency
- Manufacturing systems
- Changeability
- Design
- Digitalization/Industrie 4.0




**Learning Factory, Fig. 3** Selection of specific Learning Factory features in a morphology (Abele et al. 2015)

- Internal logistics
- Worker preparation for on-the-job training

## Cross-References


▶ Flexible Manufacturing Systems
▶ Learning Organization
▶ Manufacturing
▶ Manufacturing System
▶ Optimization in Manufacturing Systems, Fundamentals
▶ Process
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# Learning Organization


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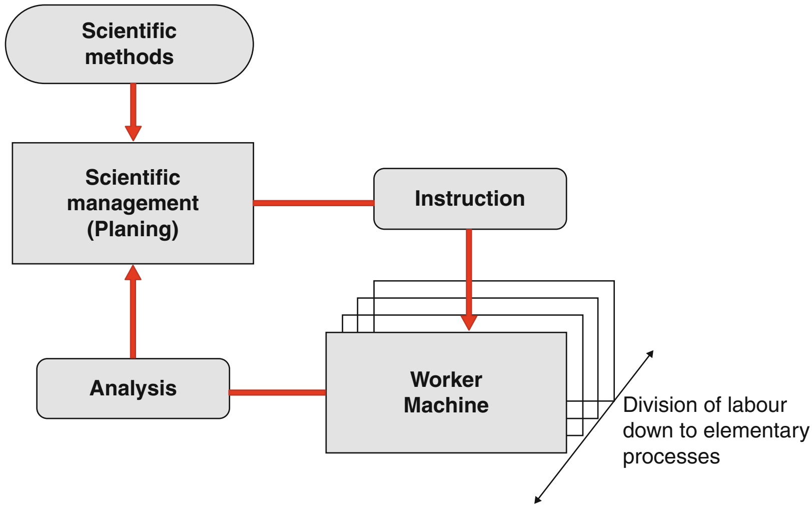
## Definition

Learning organizations have the ability for permanent optimization of processes in manufacturing by implementation of past experiences and knowledge, following "Taylors" principles as shown in Fig. 1.

A learning organization activates the experience potential by systematic monitoring of

**Learning Organization, Fig. 1** Tayloristic principle of manufacturing – learning by monitoring and instruction




processes with scientific-based methods for improvement of replicated operations and detailed instructions for operating forces (workers, machines, etc.) to achieve high performance (time, cost, quality) in socio-technical manufacturing systems.

## Theory and Application

### Learning or Experience Curve

The basic theory of a learning organization comes from the so-called "learning effect" which is described as effect of cost and time reduction as function of the number of manufactured products. Experience shows that every time total number of production units doubled, the cost and time per unit decreased on each subsequent iteration (reproduction) (Fig. 2).

This relationship was probably first quantified in 1936 at Wright-Patterson Air Force Base in the United States (Wright 1936), where it was determined that every time total aircraft production doubled, the required labor time decreased by 10–15%. Relevant publications include Henderson (1974), Hax and Majluf (1982), Berndt (1990), Chase (2001), Grant (2004), and Senge (2006).

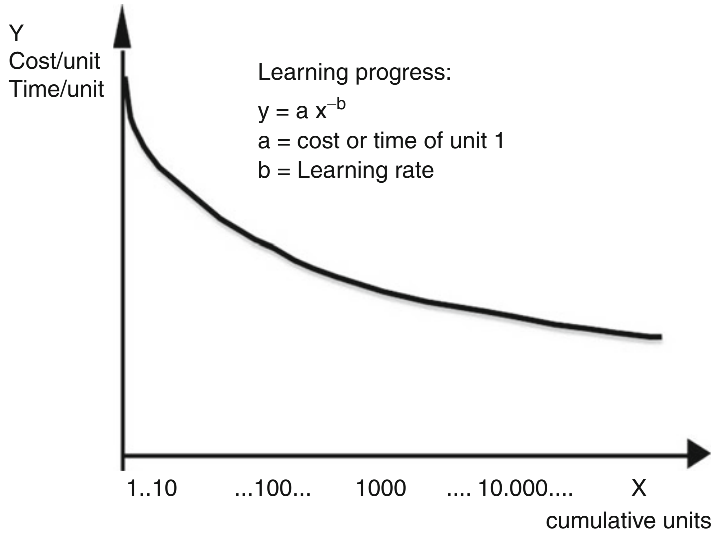
The learning rate depends on many influencing factors:

- Variety and complexity of products
- Maturity of the product design
- Skill of workers and experiences
- Automation of machines and equipment
- Application of methodologies for process optimization
- Process capability

The known effects of learning of workers are of lower impact on learning effects than the setup procedures in the ramp-up phases. The theory can be used for life cycle-oriented calculation and higher level systems to summarize all effects of learning.

### Multilevel System of Manufacturing

Manufacturing is a multilevel system (Marks 1991), as illustrated in the next figure. The system has elements, in which operations and processes create adding value and relations between the elements. The sequences of elements depend on technical and organizational requirements in chains from raw material to finished products. The flow of resources (material, energy information) links the processes and defines the relations between the elements of the system. This cooperation follows regulations of cooperation procedures in the supply chains of manufacturing in all levels. Scales of the system are:




**Learning Organization, Fig. 2** Learning as function of the cumulative number of manufactured units

- Time (from µsec, minutes, hours, days, month, years)
- Space, locations, etc.
- Material resource
- Humans (social elements)
- Information
- Elements of the system

System elements are subsystems, which even consist of sub-subsystems. This makes it possible to describe manufacturing as a multi-hierarchical socio-technical system (Westkämper 2007). The levels of the system hierarchy are:

- Manufacturing networks with elements (subsystems), factories, or segments
- Segments with elements lines, flexible systems, cells, machines
- Lines and cells with machines and working places
- Machines with machine elements (control, kinematic, etc.) and peripherals (tools, fixtures, etc.)
- Technical processes like forming, cutting, painting, joining, etc.

The axioms of system are described in Fig. 3.

Manufacturing systems are dynamic systems. They continuously change their elements and relations under the influence of the **change drivers**: products, orders, technologies, methodologies, availability of resources, etc.

## Learning Organization in Multilevel Systems of Manufacturing

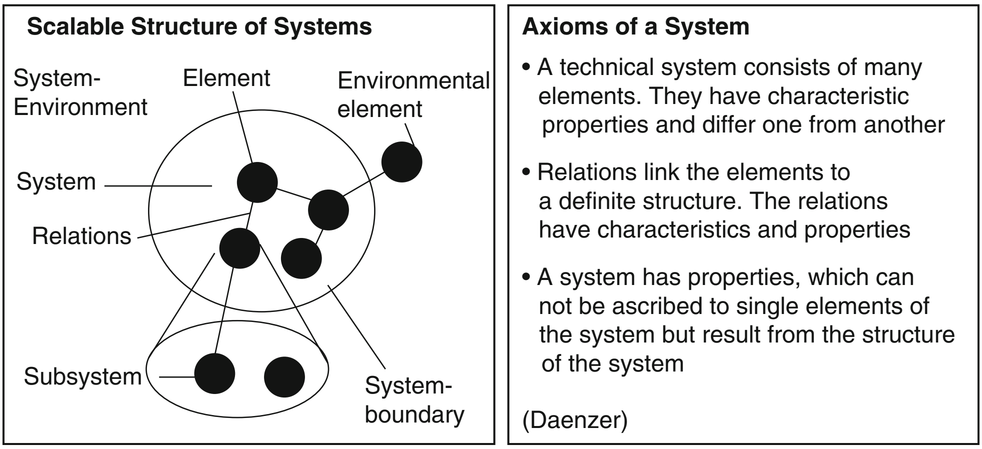
Learning effects happen in all elements and on all levels. A learning organization has specific principles and specific methodologies for activating the learning potential of the hierarchical system (Westkämper 2007). Each element has particular autonomy in the hierarchy of the overall manufacturing system and follows the principles of:

- Self-organization
- Self-optimization
- Self-control
- Self-adaptation of the operating system

The elements are integrated in an information and communication system which supports the operations with necessary instructions and process plans. Analytics for optimization are competences inside of the elements and in the system hierarchy.

## Key Applications

Learning organizations are implemented mainly in small and series production with high dynamic influences from change drivers:




**Learning Organization, Fig. 3** Multilevel system theory and axioms of a system (Daenzer and Huber 1999)

- Machine industries
- Aerospace, aircraft manufacturing
- Manufacturing of customized products

## Cross-References

▶ Flexible Manufacturing System
▶ Manufacturing System

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# Life Cycle Assessment

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## Synonyms

Cradle-to-cradle assessment; Environmental assessment of products; LCA

## Definition

The fundamental principles of life cycle assessment were laid down in the early 1990s in a scientific consensus process under the auspices of the Society of Environmental Toxicology and

Chemistry (SETAC) (e.g., SETAC 1993) and later standardized by the International Organization for Standardization (ISO) as elements of the environmental management standard series. The ISO standard for LCA defines a life cycle as: “consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal” and life cycle assessment as: “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 2006a). Environmental impacts and their assessment are treated in the (see ▶ “Environmental Impact”) and the (see ▶ “Environmental Impact Assessment”).

## Theory and Application

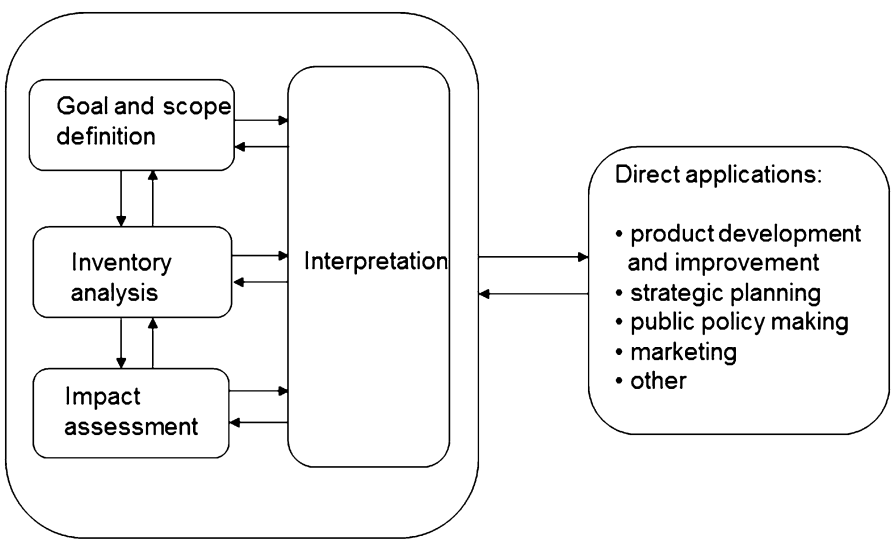
### Theory

Life cycle assessment (LCA) is an analytical method used to assess the environmental impacts of a product or a service throughout its life cycle from the extraction of raw materials over manufacture and distribution to use and maintenance and eventually end of life treatment of the product. The holistic system perspective applied on the life cycle of the product (also referred to as the “product system”) in combination with a comprehensive coverage of environmental impacts caused by the product is a central feature of life cycle assessment. They support a systematic overview that allows identifying and possibly avoiding unintentional shifting of environmental burdens between processes, life cycle stages, or different types of environmental impact.

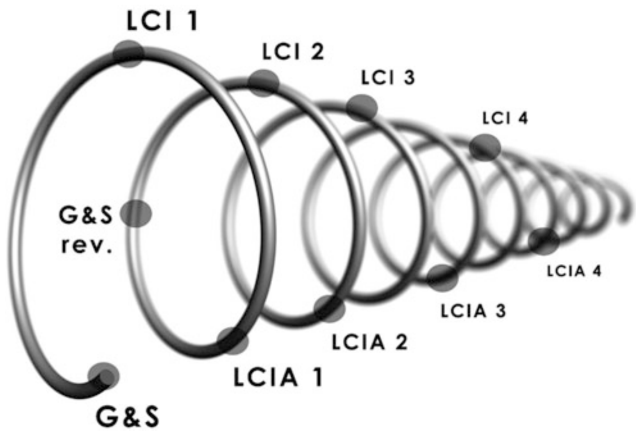
The main focus of LCA is on the environmental impacts caused by the product system although also social impacts and economic costs are analyzed in a life cycle perspective in some studies, and a framework for life cycle sustainability assessment (LCSA) has been proposed combining environmental LCA, social LCA, and life cycle costing LCC (Klöpffer 2008). The methodology for social LCA is treated by Dreyer et al. (2006, 2010a, b) and Benoît and Mazijn (2009), and LCC is addressed from a life cycle assessment perspective by Hunkeler et al. (2008). These other sustainability dimensions are not treated further in this entry.

The LCA methodology comprises the phases goal and scope definition (G&S), life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation.

As visible from Fig. 1, life cycle assessment is an iterative procedure with multiple feedback




**Life Cycle Assessment, Fig. 1** The LCA framework. (Based on ISO 2006a)




**Life Cycle Assessment, Fig. 2** LCA proceeds through multiple iterations of each methodological phase (G&S is goal and scope definition, LCI is life cycle inventory, and LCIA is life cycle impact assessment), and within each iteration the work is focused with guidance from the outcome of the previous iteration

loops between the phases. The interpretation, which is performed after each phase, includes a sensitivity analysis to determine the influence that choices made in that phase has on its outcome. This insight serves to guide a new iteration with qualification of the choices made and the data collected for central processes in the previous iteration.

### Goal Definition

The first phase of the life cycle assessment is definition of the goal of the study. This is where the LCA practitioner takes care to get the question right before starting to answer it with the assessment. It is a very important phase influencing central choices to be made in the ensuing scope definition, and framing the interpretation of the results, which should always be done in respect of the defined goal of the study. For further details see the ► "Life Cycle Assessment: Goal and Scope Definition".

### Scope Definition

Based on the defined goal, the life cycle assessment is scoped in terms of six aspects.

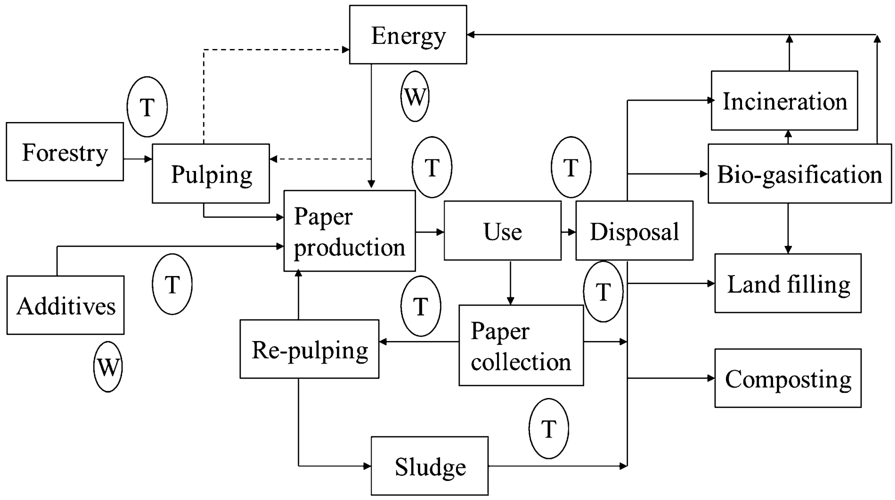
1. *The product system to be studied*

   This is where the boundaries of the product system (example in Fig. 3) are drawn and decisions made on which processes need to be included and which processes can be left out, considering the goal of the study. The choices made when drawing the boundaries are later checked when results of the inventory analysis and impact assessment are available (as illustrated in Fig. 2).
2. *The functions of the product system and the functional unit of the study*

   When the LCA is used for comparative purposes (which is very often the case), it is essential that the compared alternatives are *true alternatives*, i.e., they are seen as functionally equivalent by the user of the product or service that is studied. This is ensured by anchoring the LCA in a functional unit – a quantitative description of the service to be offered by the analyzed product systems.
3. *Types of environmental impact to be analyzed*

   The LCA practitioner must up front choose which environmental impacts the study should address, so the relevant information about the product system can be gathered during the later inventory analysis. It is a requirement in the ISO standard that the chosen selection of impact categories reflects a comprehensive set of environmental issues related to the product system being studied (ISO 2006b).
4. *Handling of multifunctional processes (allocation procedures)*

   In most product systems, there will be processes that have several valuable outputs (often termed co-products or by-products), of which some are not used by the studied product system (i.e., they do not contribute to the functional unit of the study). This means that not all




**Life Cycle Assessment, Fig. 3** Process tree illustrating the life cycle of paper for newsprint or office use. "T" and "W" represent transportation and waste treatment processes, respectively, with life cycle of their own, not shown in the figure

the environmental impact from the multi-functional process should be carried by the studied product system; other product systems should carry part of the impact. The ISO standard offers a hierarchy of solutions to this challenge (ISO 2006b).

5. *Fundamental approach to the modeling of the inventory (attributional or consequential)*

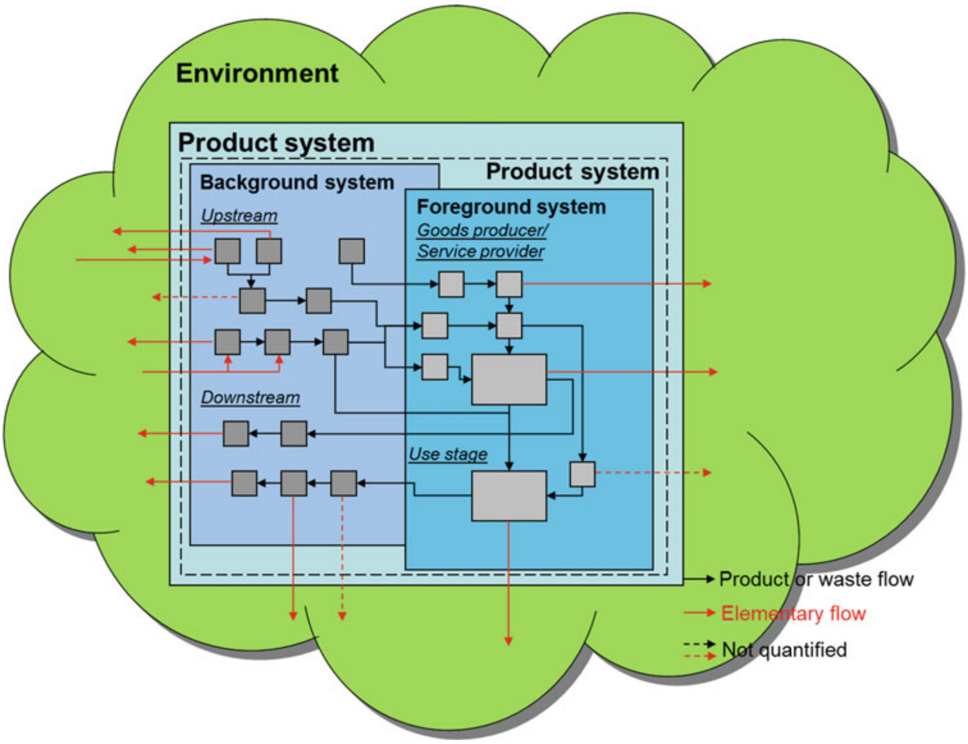
   Depending on whether the LCA is performed with the purpose (as defined in the Goal definition) to support decisions and choices between alternative products or with the purpose to document the environmental impacts associated with a product or a service, different modeling approaches are recommended in the inventory analysis. The former requires a consequential approach (in simple terms analyzing the consequences of the decision for the product system and the resulting environmental impacts, typically using market information to identify the marginal technologies that are affected by the decision). The latter calls for an attributional approach (accounting perspective, typically applying average data for the involved technologies).

6. *Type of critical review, if any, and type and format of the report required for the study.*

Considering the complexity of most product systems and the number of choices that are made in an LCA, a critical review by an expert outside the study is normally a good idea. For publicly communicated LCA studies that claim to be compatible with the ISO standard, a critical review is a requirement of the standard that gives guidance on how to perform the review.

### Life Cycle Inventory, LCI

The life cycle inventory phase follows the scope definition and consists in a compilation of input and output flows from all the processes in the product system. The product system can be divided into a foreground system, comprising all the processes under influence of the producer of the product or the provider of the service, and a background system on which the foreground processes draw. The background system comprises processes that are not directly controlled by the producer or immediate suppliers such as raw material extraction, production of materials and standard components, transportation, supplies of electricity and water, and treatment of waste. The concept of foreground and background system is illustrated in Fig. 4.




**Life Cycle Assessment, Fig. 4** The product system can be split into a foreground system and a background system according to the influence of the producer or provider of the service

For processes belonging to the foreground system, it is normally possible for the producer of the product to obtain primary data representing the actual processes that are active in the product system. These can be obtained through measurements on own processes and inquiries to suppliers. Depending on the goal of the study, primary data should be sought for the dominating processes in the foreground system.

For processes belonging to the background system, it is generally not possible and often not relevant to decide the precise process that is active in the product system. For commodities traded in a market it may fluctuate with time and location, and often, an average across technologies is used, e.g., for the technology used to generate the electricity or incinerating the waste from the product system.

Unit process databases offer data on input and output for many technical processes presented per functional output of the process (e.g., per kWh for electricity generation, per mass for production of materials like plastics, or per weight and distance for transportation processes). These serve as building blocks that can be scaled to the relevant size when the product system is modeled.

The inventory can be reported per life cycle stage or for the whole product system as a list of elementary flows per functional unit.

### Life Cycle Impact Assessment, LCIA

Even for simple product systems, LCI easily comprises hundreds of elementary flows in the form of resource input, land and water use, and emissions to the different compartments of the environment – air, water, and soil. Some flows are large and some are small, and their ability to cause environmental impact can vary dramatically. In order to interpret the outcome of the inventory analysis in accordance with the goal of the LCA, it is necessary to incorporate knowledge about the environmental properties of the elementary flows. This is the objective of the impact assessment phase of LCA.

According to the LCIA framework laid out in the ISO standard, the impact assessment proceeds through a number of steps:

First the categories of environmental impact to address are defined or – typically – chosen among already defined and developed categories of impact (see ► "Environmental Impact" for default list of impact categories in LCIA). Then the elementary flows from the inventory are assigned to the different categories of impact, each of which is represented by an impact indicator. This step is called classification of the inventory flows.

Next step is characterization where a quantification of the contribution of the elementary flows to the total impact score for the category is calculated using characterization factors. A characterization factor is a quantitative expression of the substance's specific ability to impact on the indicator of the impact category, determined by the inherent properties of the substance. The resulting indicator scores are summed across elementary flows within the impact category, and the collection of category indicator results for the different impact categories is the environmental impact profile of the product.

The indicator can be chosen anywhere along the impact pathway from inventory result to the final endpoint, human health, natural environment, or natural resources. Figure 5 lists the typical midpoint impact categories (i.e., category indicator chosen at some point between the elementary flow of the inventory and the resulting damage to an area of protection in the form of human health, environment, or resources). It also indicates how each of the impact categories relates to the areas of protection.

A number of LCIA methods have been developed over the last 20 years. Hauschild and Huijbregts (2015) give a recent and consistent presentation of most of the existing LCIA methods.

The third and fourth steps of the LCIA are voluntary and support comparison across impact categories. The third step is normalization, where the indicator results from the characterization step are related to a common set of reference information, frequently the current level of impact from society within each impact category. Normalization brings all scores on a common scale, expresses them in a common metric, hereby making it easier to relate them to each other and preparing for the likewise voluntary valuation or weighting.

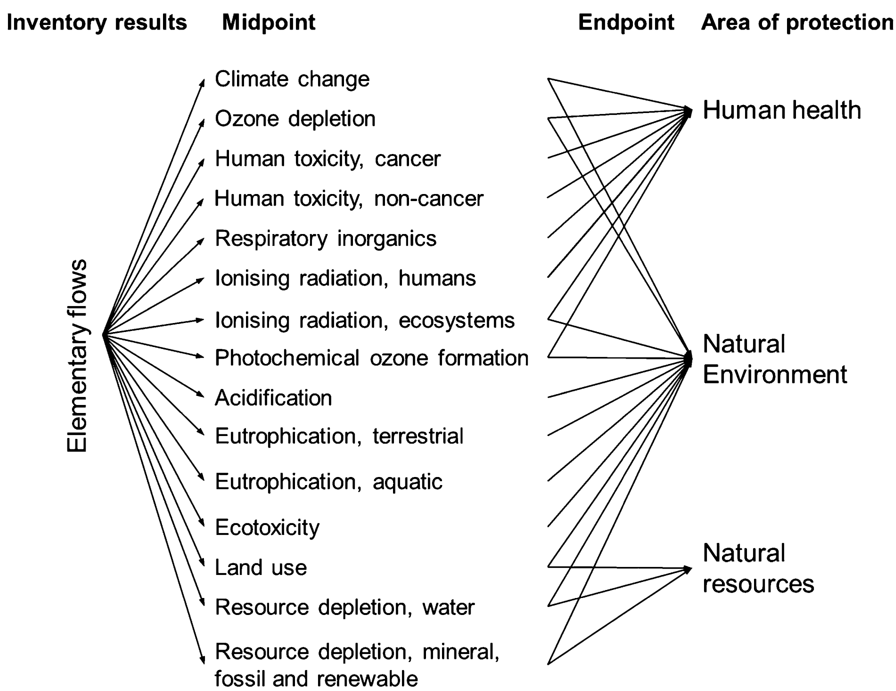
Valuation is the fourth and final step of the LCIA. It may be performed in comparative LCAs none of the compared alternatives is the absolute preference, outperforming the others on all category indicator results. It can be done as a weighting assigning quantitative weights to all category indicators, but it can also be a more qualitative ranking or grouping of the category indicators. It involves subjective choices, and in LCA studies supporting comparative assertions disclosed to the public the ISO standard does not allow the use of weighting (ISO 2006b).

### Interpretation

The last phase of the life cycle assessment methodology is the interpretation phase where the results of the other phases are interpreted in accordance with the goal of the LCA. Sensitivity and uncertainty analysis are important elements in the interpretation and as illustrated in Figs. 1 and 2, these elements of the interpretation are performed throughout the analysis as the guiding element of the iterative approach that is fundamental in LCA. The conclusions that come out of the interpretation should respect the intentions and restrictions of the goal and scope definition of the study. The interpretation should present the results of the LCA in an understandable way and help the reader evaluate the robustness of the conclusions and understand the weaknesses of the study in light of the identified limitations.

## Application

The ability of LCA to quantify environmental impacts of products and services is utilized for




**Life Cycle Assessment, Fig. 5** Impact categories according to the European Commission's ILCD guidelines (Hauschild et al. 2013)

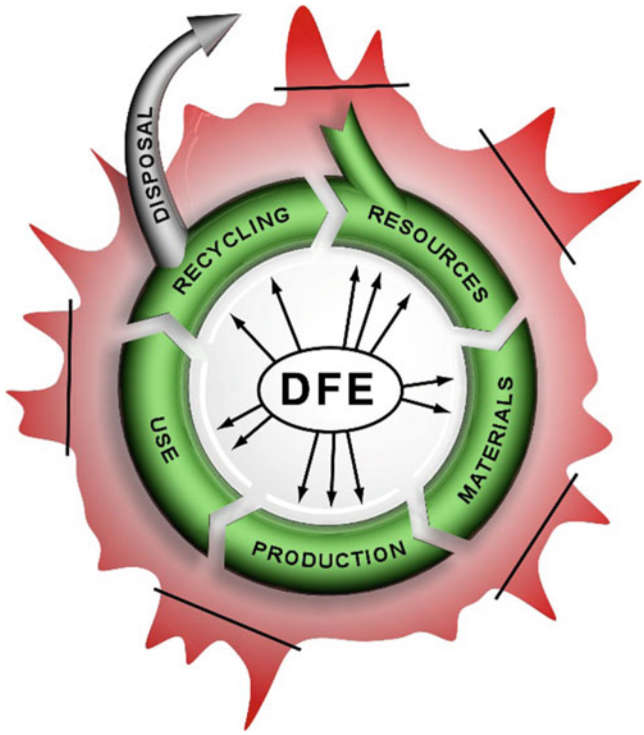
various purposes by different sectors in society. Hauschild et al. (2017) reviewed LCA application practices within multiple decision contexts and technological sectors.

### Industry

With the growing concern about environmental sustainability and the outsourcing of manufacturing, the responsibility of industry has expanded from its own facilities to encompass the whole value chain. With product stewardship and the focus on circular economy, the environmental performance in the use stage and end of life stage of the product also increasingly becomes the responsibility of the company. Accordingly, sustainability claims have to consider the whole life cycle of the products or services of the company, and this makes LCA a central tool for gauging the environmental sustainability performance of an industry. Important fields of application are product development, product documentation and marketing, and company reporting.

**Product development – design for environment.** Incorporation of environmental performance in the development of products has long been an important internal use of LCA in many companies. LCA helps determine the environmental impact hot spots in the product and in its life cycle identify focus points for the product improvement and set targets for the product development. During the product development LCA-based tools are used to analyze and compare alternative solutions and document the attained improvements (Fig. 6).

**Environmental product information and marketing**. Companies that want to use the environmental performance attributes in the marketing of products may use Environmental Product Declarations (EPDs), which have the results of a life cycle impact assessment as a core element together with other relevant environmental information about the product (International EPD System 2017).




**Life Cycle Assessment, Fig. 6** LCA-based insights help focus ecodesign (design for environment, DFE) on the environmental hotspots in the product and its life cycle

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**Company reporting**. Outsourcing introduces a risk of problem shifting. The environmental impacts from the company's own activities are reduced, but impacts from the suppliers may be worse for the same produced output. Through its contracts with suppliers, the company can influence their environmental performance, and this entails a responsibility for this part of the life cycle as well. It is therefore relevant to include the value chain in environmental sustainability reporting, and many companies do that, e.g., in their reporting on environmental performance indicators like the company's carbon footprint or environmental footprint, taking a life cycle perspective on their activities, and quantifying the associated impacts in a life cycle perspective. Some companies (e.g., Puma sport goods and Novo Nordisk pharmaceuticals) have taken the step to calculate and report on the "true cost" of their products or activities, quantifying the environmental impacts in the value chain (the "externalities" in economic terms), monetarizing them, and including them as economic costs in the economic accounting for the product or the company to reveal its net economic value to society (Trucost 2017).

## Authorities

Historically, public regulation of environmental pollution has focused on the most important point sources like heavily polluting industries, mines, or landfills. Some of the most challenging environmental impacts that our societies face today are, however, of a more diffuse nature. They are caused by activities or emission sources that each alone has a very small impact, that can be difficult to trace to the source (hence "diffuse"), but that occur in huge and often growing numbers which causes the problem. An example is climate change impacts where an important cause is our use of fossil-based energy for transportation, use of electrical products, or heating of houses. Another example is the use of ten thousands of chemicals in the products that we find in the market today and the emission of these chemicals to the environment from manufacturing, use, and disposal of the products. Taken one by one, most of these chemicals may not constitute an environmental problem but together they can lead to exposure of ecosystems or humans in exceedance of safe levels. Given the role that consumption of products has in the growth of these environmental problems, it is natural that authorities have looked toward the products and their regulation in search for a way to control them, and the last decades have seen the development of sustainable consumption and production strategies to support sustainable development at the regional as well as the global level (EC 2017; UNE 2017).

For quantitative information about the environmental performance of products LCA is the tool of choice. The European Commission has introduced the term "Product Environmental Footprints (PEFs)" for the results of product life cycle impact assessments. In order to harmonize the results of life cycle assessments and strengthen their use in policy contexts, a PEF guideline has been developed and operationalized in a number of Product Category Rules simplifying and harmonizing the LCA work by stipulating methodological details in the assessment approach to be taken for different product categories (PEF World Forum 2017).

In accordance with the ISO standard for ecolabeling (ISO 1999), life cycle assessments are also used in the development of criteria for ecolabels in many parts of the world. The LCA results are used to identify the most important causes of environmental impact for the product category in question, and determine desirable performance levels for these aspects, so the ecolabel criteria can target them. Together with environmental product declarations (see above), ecolabels are used to inform both professional public purchasers and ordinary consumers.

### Consumers

Consumers use LCA-based information to make informed choices among alternative products or services, when they wish to behave as green consumers and favor the producers that offer the greenest products. The information is typically offered in the form of ecolabels but also environmental product declarations and similar information is increasingly becoming available to the interested consumer.

## Cross-References


- ▶ Environmental Impact
- ▶ Life Cycle Assessment: Goal and Scope Definition
- ▶ Life Cycle Impact Assessment
- ▶ Life Cycle Engineering
- ▶ Product Life Cycle Management


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# Life Cycle Assessment: Goal and Scope Definition

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## Definition

The goal and scope definition is the first phase of the life cycle assessment (LCA) methodology according to the ISO standard for LCA (ISO 14040 2006; ISO 14044 2006). The overall LCA methodology and its applications are treated in the entry on ► Life Cycle Assessment.

## Theory and Application

The LCA methodology comprises four methodological phases among which the goal and scope definition (G&S) is the first as illustrated in Fig. 1. The G&S phase is where the study is defined and central choices made regarding its conduct.

### Goal Definition

The first consideration in the life cycle assessment of a product or technical system is the definition of the goal of the study. This is where the question to be answered by the LCA is formulated, and it is essential to get this question right to ensure the relevance of the study. The goal definition is thus a very important consideration, and it strongly influences central choices that are made in the ensuing scope definition and frames the later interpretation of the results, which should always be done in respect of the defined goal of the study.

Examples of goal definitions are:

> "The goal of the study is to determine the parts of the life cycle that contribute most to the overall environmental impacts of the product to help focusing the development of a product with a lower environmental impact."

> "The study is performed to serve as basis of an environmental product declaration of the product to be used in the marketing."

### Scope Definition

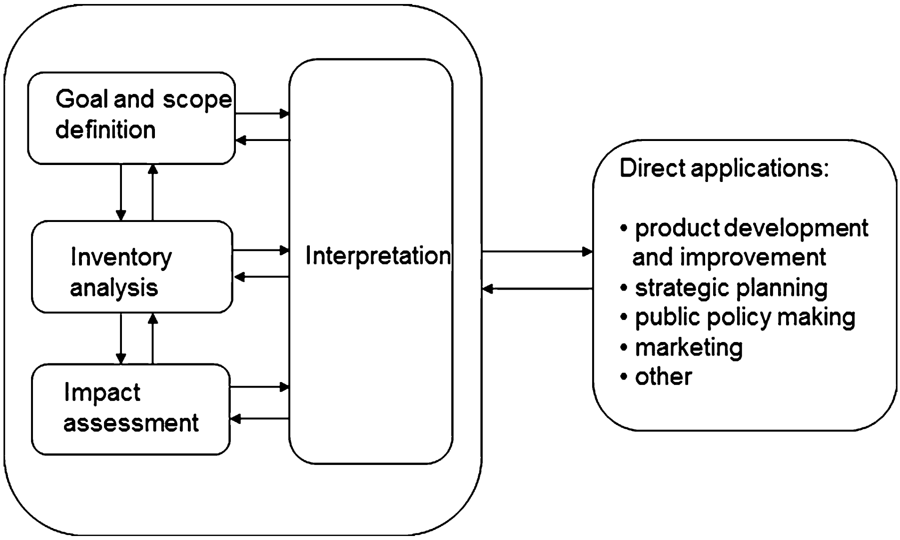
Based on the defined goal, the life cycle assessment is scoped in terms of central aspects and choices encompassing:

1. The product system to be studied
2. The functions of the product system and the functional unit of the study
3. Types of environmental impact to be analyzed
4. Handling of multifunctional processes (allocation procedures)
5. Fundamental approach to the modelling of the inventory (attributional or consequential)
6. Type of critical review, if any, and type and format of the report required for the study

Each of these elements is discussed in larger detail in the rest of this entry.

#### The Product System

The product system comprises all the processes that are involved when the product goes through its life cycle. It goes from the cradle to the grave, i.e., from the extraction of resources over their conversion into materials and components to the manufacture of the product, its distribution and its use and maintenance, and further on to its end of life in the form of reuse, remanufacturing, or recycling or disposal through incineration or landfilling. Figure 2a, b show different ways of illustrating product life cycles.




**Life Cycle Assessment: Goal and Scope Definition, Fig. 1** The LCA framework (Based on ISO 14040 2006)

### The Functional Unit and the Reference Flow

Life cycle assessment is often used in comparison of the environmental impacts associated with different products or different ways of solving a problem or providing a service. To ensure a relevant and fair comparison, it is essential that the functionality offered by the alternatives is comparable. In order to ensure this, the service to be provided by the analyzed product or system is defined scrupulously in quantitative terms in the functional unit of the study. The functional unit typically describes the service and quantifies its extent and duration. The quality of the way in which the service is offered may additionally be described in an unambiguous way in the functional unit by referring to technical standards for that type of service.

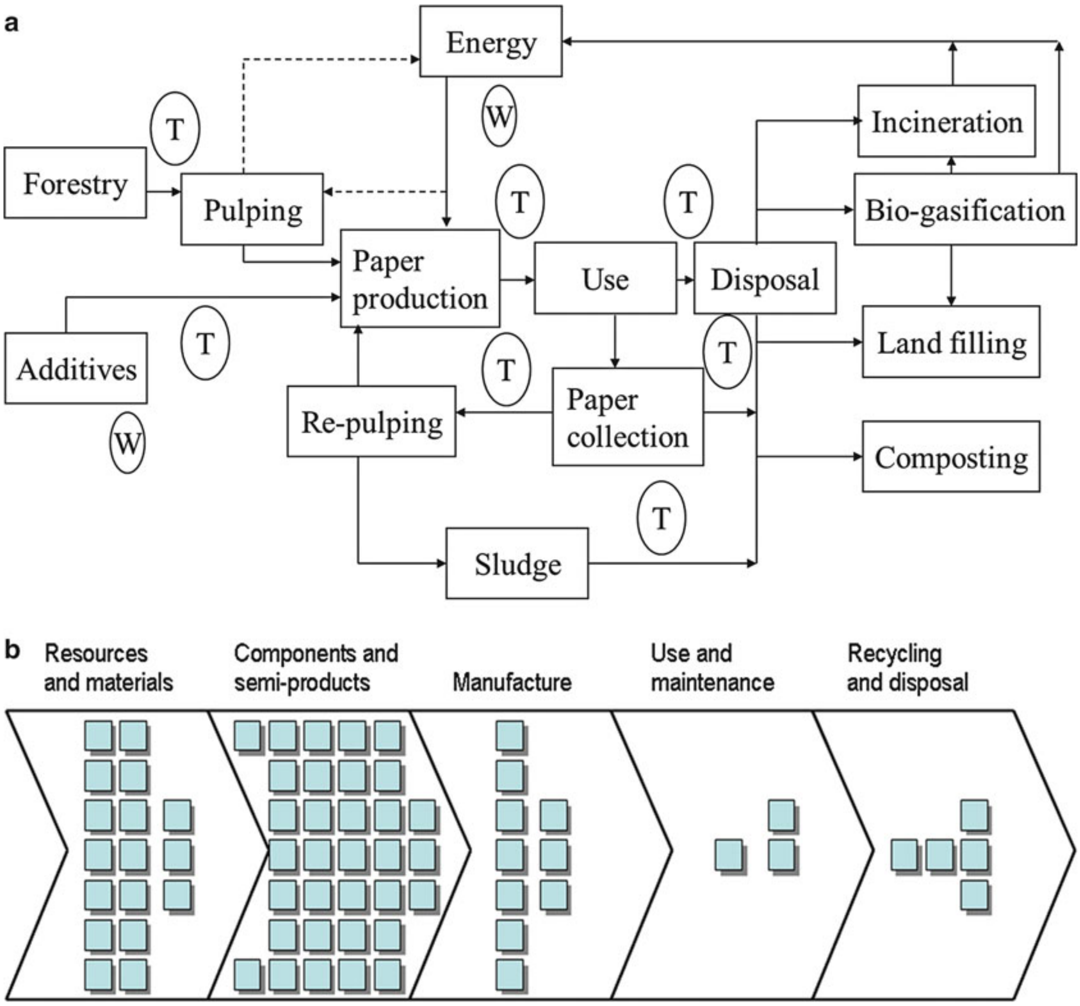
For an outdoor paint, the functional unit could be to cover a 10 $m^2$ concrete wall facing west for 5 years and protect it against the climate while retaining its original color.

The way in which the wall is protected and the color of the paint is retained throughout the 5 years should be defined through referring to relevant technical standards for outdoor paints.

Based on the functional unit, the quantity that is needed of each of the compared alternatives can be quantified. This quantity is the *reference flow* of the study and represents the quantity that needs to be processed by all processes in the product system. In the inventory analysis of the study, the input flows and the emissions of waste and pollutants, which are caused by the processing of the reference flow, are quantified.

### Environmental Impact Parameters

LCA is performed to analyze the environmental impacts of the product system, and in the scoping of the study, it is required to determine which impacts should be covered in order to ensure collection of the relevant data for the product system. The ISO standard for LCA requires that the selection of impact categories reflects a comprehensive set of environmental issues related to the product system being studied (ISO 14044 2006). This means that a study exclusively focusing on one category of impact like carbon footprint or water footprint studies is not considered life cycle assessments in the sense of the ISO standard although they do analyze the full product system. The requirement of a comprehensive coverage of environmental impacts serves to ensure that any environmental problem shifting (improving the performance in terms of, e.g., climate change at the expense on a poorer




**Life Cycle Assessment: Goal and Scope Definition, Fig. 2** (**a**) Process tree illustrating the life cycle of paper for newsprint or office use. "T" and "W" represent transportation and waste treatment processes, respectively, with life cycle of their own, not shown in the figure. (**b**) Schematic presentation of product system with the processes (each blue box represents a process) divided into five life cycle stages



performance in, e.g., land use or ecotoxicity) will be revealed by the LCA.

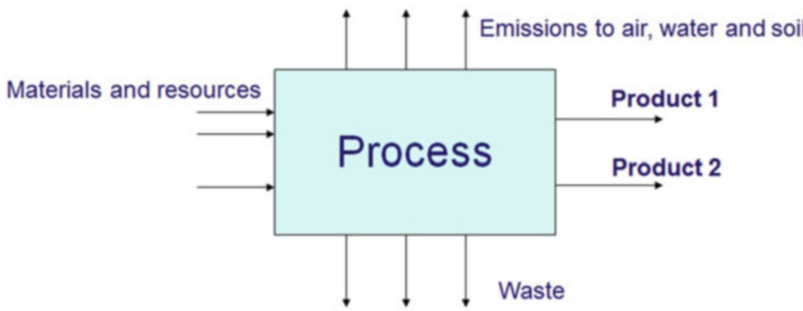
### Handling of Multifunctional Processes

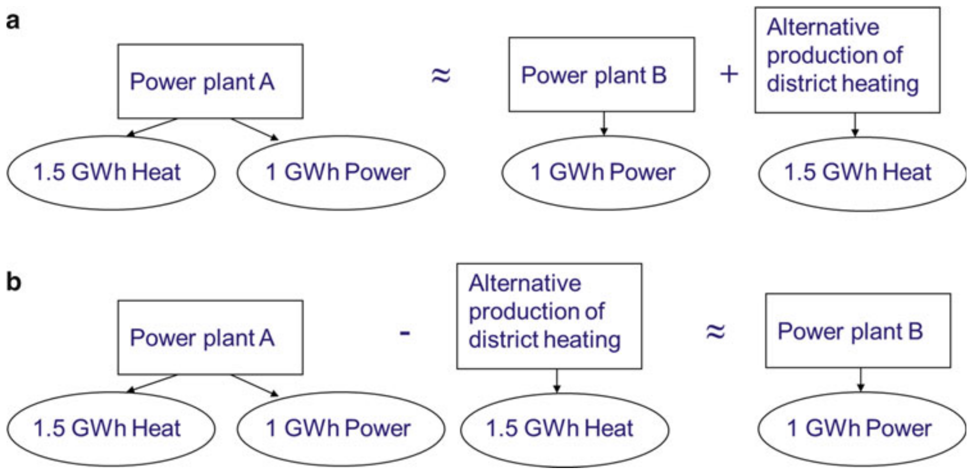
There is often an economic incentive to try to utilize by-products of a process so that they become commodities rather than an unwanted waste. Most product systems therefore include processes that provide more than one valuable output – so-called multifunctional processes (see Fig. 3). When a product system includes a multifunctional process, the inventory modelling of an LCA must address the issue that, if only some of the valuable outputs of the process contribute to the functional unit of the LCA, it is also the only part of the environmental burdens of that process that should be assigned to the functional unit.

There are two fundamentally different ways of handling multifunctional processes in LCA: system expansion and allocation

**System expansion** is applied in order to ensure that the alternatives that are compared in the LCA offer the same functionalities, i.e., not just the same primary functionality, as described in the

**Life Cycle Assessment: Goal and Scope Definition, Fig. 3** A multifunctional process yields more than one product (or service), and all input of materials and resources output of waste and emissions cannot be assigned to just one of these products




**Life Cycle Assessment: Goal and Scope Definition, Fig. 4** System expansion and crediting of avoided impacts illustrated for an LCA comparing electricity production at a thermal power plant with (**a**) and without (**b**) cogeneration of heat and power

functional unit, but also for any secondary functionality coming from the multifunctional processes. With the process in Fig. 3, the product system has a secondary functionality by delivering product 2. To make the analyzed systems functionally equivalent, the other product system must be expanded in a way that allows it to provide this secondary functionality as well. This is done by identifying the most probable alternative way of providing the secondary functionality which is offered by product 2 and including the processes that are involved in this alternative way in the study of the other product system. This is illustrated in Fig. 4 for a comparison of electricity production at a thermal power plant with (a) and without (b) cogeneration of heat and power.

As illustrated in Fig. 4, system expansion is equivalent to crediting with the flows that are avoided when the secondary functionalities offered by the multifunctional processes are utilized outside the product system. Both power plants in the figure produce 1 GWh of electricity (the reference flow of the study), but Power plant A additionally produces 1.5 GWh district heating as a secondary function by utilizing the waste heat. To make the systems functionally equivalent, the system with Power plant B must be expanded with processes representing the most probable alternative way of producing this heating service as illustrated in Fig. 4a. Another way of viewing this is that when Power plant A with the cogeneration of heat and power is chosen, the alternative production of heating with its associated inputs of fuels and outputs of environmental emissions and residual products is saved, and the product system of Power plant A should be hence credited with these savings as shown in Fig. 4b. The ISO standard gives preference to system expansion for handling of multifunctional processes (ISO 14044 2006).

**Allocation**. Sometimes it is not possible or practical to perform a system expansion, and then the ISO standard prescribes an allocation of the input and output flows of the multifunctional process between its products, i.e., a division of the flows according to an allocation key. The allocation key should preferably be a governing joint technical property of the products. In the example from Fig. 4 with cogeneration of heat and power in a thermal power plant, the resource input and emissions may be allocated between the produced heat and power in proportion to their energy content. Often it is not possible to find a common governing joint technical property on which to base the allocation, and then the ISO standard recommends basing the allocation on a measure of the economic value of the products (ISO 14044 2006).

### Attributional or Consequential Approach

Life cycle assessment can be performed to support decisions and choices between alternative products or to document the environmental impacts associated with a product or a service.

In the first case, the goal of the LCA will often be to show the environmental consequences of the decision. The systems to be modelled are then the systems that will result from the choice. This means that the processes that are modelled in the product system should be the processes that are affected by the choice to be made (the marginal processes). When multifunctional processes occur, the system expansion is the preferred approach under a consequential approach since it aims to model what is replaced as a consequence of the secondary output of the multifunctional process. These are the main characteristics of the *consequential approach* to LCA.

In the second case, the purpose is to quantify the environmental impact that has been caused by the product or activity (often a more retrospective perspective) throughout its life cycle. Even though decisions will often be based on this type of information as well, there is no concrete decision context identified. For the background processes in the product system (processes that are only insignificantly affected by changes in the studied product system and not under control of the producer of the studied product or service), average data is typically applied. For multifunctional processes, allocation is preferred to determine the share of the burdens to be assigned to the product system.

A discussion of attributional and consequential approaches and their relation to different decision situations (as defined in the goal definition) is given in the guidelines for LCA from the International Reference Life Cycle Data System, EC-JRC (2010).

### Critical Review and Reporting Issues

Product systems are complex entities, and many choices have to be made when they are modelled. A critical review of the LCA is therefore always useful to ensure the reliability of the study, but the ISO standard requires a critical review for publically communicated LCA studies that claim to be compatible with the standard in order to ensure that:

– The methods used to carry out the LCA are consistent with the standard.
– The methods used to carry out the LCA are scientifically and technically valid.
– The data used are appropriate and reasonable in relation to the goal of the study.
– The interpretations reflect the limitations identified and the goal of the study.
– The study report is transparent and consistent.

When the results of the LCA are intended to be used to support a comparative assertion to be disclosed to the public, the ISO standard has stronger requirements to the composition of the review panel, which must include interested parties who may suffer negative effects from the communication (ISO 14044 2006).

## Application

Goal and scope definition constitute the first phase of a life cycle assessment and as such are only applied as part of a full LCA.

As visible from Fig. 1, life cycle assessment is an iterative procedure with multiple feedback loops between the phases. The interpretation, which is the phase where the outcomes of the

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other phases are interpreted to answer the question that was posed to the LCA, thus has to carefully consider the goal definition and respect it when the results are interpreted to avoid conclusions that go beyond what the study supports.

A thorough introduction to the goal and scope definition phase of LCA is given in Hauschild et al. (2017).

## Cross-References

▶ Life Cycle Assessment
▶ Life Cycle Impact Assessment

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# Life Cycle Cost

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## Synonyms

Life cycle cost analysis; Total cost of ownership; Whole-life cost

## Definition

The definition of LCC as quoted from AS/NZS 4536:1999 (Australian/New Zealand Standard 1999) is a process to determine the sum of all expenses associated with a product or project, including acquisition, installation, operation, maintenance, refurbishment, discarding and disposal costs.

Life cycle costing (LCC) is a concept for estimating the total cost or total ownership cost (TOC) which includes acquisition costs (total capital cost, i.e., land acquisition costs and construction costs) and ownership costs (all future costs, viz., installation costs, operation costs, repair costs, service and maintenance costs, and disposal costs), as well as other cost components.

The acquisition costs are often visible as they relate to purchasing assets such as equipment, which include the investment for the raw material cost and up until the equipment is manufactured and has left the factory. The acquisition cost is genuinely the tip of an iceberg as there are other future costs which are incurred after the product is manufactured such as the transportation, handling, installation, maintenance, and end-of-life costs.

## Theory and Application

### History

LCC was developed by the US Department of Defense (DOD) during the mid-1960s and has been used ever since as a tool for large infrastructure projects such as military facilities, buildings, and oil refineries. From the 1980s to the early 1990s, different cost models were developed for LCC estimation, among them, Activity-based life-cycle costing in 2001 (Emblemsvag 2001).

In the 2000s, the list of LCC applications was extended to include more products and processes, and LCC was integrated into other aspects of sustainability including environmental life cycle costing (ELCC) and societal life cycle costing (SLCC). These two types of LCC are different than the conventional LCC as they integrate LCC with the environmental aspect of LCA (Hunkeler et al. 2008).

The SLCC may also include externalities or external costs as defined by environmental economics and external costs which are usually borne by society. Such costs can be assessed using the preference theory of economic valuation methods (e.g., hedonic pricing and contingent valuation) that are based on the market and nonmarket values (e.g., the willingness-to-pay survey) (Rebitzer and Hunkeler 2003).

### Potential Benefits

LCC leads to potential benefits in the long term since manufacturers can gain revenue during the usage and end-of-life stages with an appropriate decision at the design stage. It can be applied at any stage of the product life cycle, but when it is applied at the early, conceptual, and detailed design stage of product development, 70–85% of the total cost of a product can be saved.

## Theory

### Goal and Purpose

In principle, LCC uses the same principal as cost accounting calculation that is based on real monetary flows. The main goal of LCC is to compare the TOC for different product or process alternatives. It is used as an engineering decision-making to identify the most cost-effective decision when considering the costs and the revenues involved during all life cycle stages, namely, material, manufacturing process, usage, and end-of-life. ISO15663, IEC60300-3-3, and AS/NZS 4536 are the main procedures for LCC methods (Hunkeler et al. 2008).

LCC is also used as a tool for triple-bottom-line assessment of the sustainable development where win-win situations and trade-offs are identified by considering LCC in conjunction with life cycle assessment (LCA) and its social impact such as the externalities.

### Life Cycle Costing Methodology

Many LCC models and methods have been developed over the years as a tool to support the economic decision-making.

Life cycle cost models can be categorized into three categories (Dhillon 2010) which are:

1. *Conceptual models*: This category is for macro-level. It is flexible and based on qualitative variables and hypothesis approach (Sherif and Kolarik 1981).
2. *Analytical models*: Mathematical models in this category are ranging from simple to very complex models, and they are considered as the most commonly used cost models.
3. *Heuristic models*: The model can involve simulation models but cannot guarantee to give an optimum solution. These models are based on an ill-structured version of analytical models: an experience-based method and rule-of-thumb strategy, for example, a simulation technique that determines the cost-effectiveness of different levels of reliability and maintainability training for airlines.

### Life Cycle Cost Basic Steps

Life cycle cost can be analyzed by using the following basic steps (Dhillon 2010):

1. Cost breakdown structure (identify activity and define cost drivers)
2. Cost estimating (present value)
3. Discounting
4. Inflation

*Cost breakdown structure* (*CBS*): This is the most important step as it identifies all the associated cost elements as well as establishes the boundary of the LCC analysis. This is to prevent any omission and double counting of the cost elements.

*Cost estimating*: Each cost element has to be estimated which can be performed by using the following three approaches:

- The first approach is when the factors of the cost elements are known with a known accuracy level.
- The second approach is predicting by using the historical or empirical data.
- The third approach is the expert opinion which is used when there is no real data. The opinion must be supported with the assumptions made.

All costs including the future cost such as the maintenance and disposal costs are converted into present values.

**Life Cycle Cost, Table 1** Corporate environmental accounting tools (modified) (Gluch and Baumann 2004)

| Concept | Definitions/description | Cost categories |
|---|---|---|
| Full cost accounting (FCA) | Identifies and quantifies the full range of costs throughout the life cycle of the product, product line, process, service, or activity (Spitzer et al. 1993) | Identifies and quantifies (1) direct, (2) indirect, and (3) intangible costs |
| Full cost environmental accounting (FCEA) | Embodies the same concept as FCA but highlights the environmental elements (US EPA 742-R-95-001 1995) | Varying |
| Total cost assessment (TCA) (I) | Long-term, comprehensive financial analysis of the full range of internal costs and savings of an investment (White and Becker 1992; Spitzer et al. 1993) | (1) Internal costs and savings |
| Total cost accounting (TCA) (II) | Term used as a synonym for either the definition given to FCA or as a synonym for TCA (Spitzer et al. 1993) | (1) Conventional costs, (2) hidden costs, (3) liability costs, (4) less tangible costs |
| Life cycle accounting (LCA) | The assignment or analysis of product-specific costs within a life cycle framework (EPA 1993) | (1) Usual costs, (2) hidden costs, (3) liability costs, (4) less tangible costs |
| Life cycle cost assessment (LCCA) | Systematic process for evaluating the life cycle cost of a product or service by identifying environmental consequences and assigning measures of monetary value to those consequences (Warren and Weitz 1994; Bennett and James 1997). LCCA is a term that highlights the costing aspect of life cycle assessment (LCA)[a] (Spitzer et al. 1993) | Adding cost information to LCA |
| Life cycle costing (LCC) (I) | Summing up total costs of a product, process, or activity discounted over its lifetime (EPA 1993; Henn 1993; Spitzer et al. 1993; US EPA 742-R-95-001) | Varying |
| Life cycle costing (LCC) (II) | A technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial costs and future operational costs [ISO15686][b] | Varying |
| Full cost pricing (FCP) | Term used as a synonym for FCA or LCC (Little 2000) | See FCA and LCC |
| Whole-life costing (WLC) | Synonym to TCA (I) or LCC (Sterner 2002). More specifically designed by Clift and Bourke (1999) as "The systematic consideration of all relevant costs and revenues associated with the acquisition and ownership of an asset" | (1) Initial costs and (2) operational costs |

[a]Life cycle assessment (LCA) – an environmental management tool for evaluating the environmental impacts of products and services from cradle to grave in their life cycles (Baumann and Cowell 1999)
[b]This definition is not developed in an environmental context; it is defined in a building and construction asset standard [ISO15686]

*Discounting*: This is defined as a percentage of the value of money that is changed over time between the present and future.

If the percentage is set in a high value, then the importance gives more to the present time. If the percentage is low, then the future is considered to be more important. When the percentage is equaled to zero, this means there is no difference in the value between the present and the future.

The discount value depends on many variables such as inflation, cost of capital, investment opportunities, and personal consumption preference. These values must be validated carefully with a careful expert consultation.

*Inflation*: This is often excluded from LCC; however, it is considered when there is more than one commodity such as oil price and man-hour rates.

Additionally, the sensitivity analysis should be conducted to examine the uncertainty of the cost model.

### Life Cycle Cost Elements

Cost elements of LCC are defined in various definitions such as internal and external costs and direct and indirect costs. Among the definitions, the total cost assessment method, which is one of LCC methods, classifies costs into five categories (Little 2000). These are:

- The direct costs for the manufacturing site (e.g., capital investment)
- The potentially hidden corporate and manufacturing site overhead costs (indirect, e.g., outsourced services)
- The future and contingent liability costs (e.g., liabilities for personal injury and property damage)
- The internal intangible costs (e.g., customer loyalty and corporate image)
- The external cost (social cost)

These cost elements may include both nonrecurring (one-off, e.g., installation and facility) and recurring costs (e.g., maintenance and handling).

### Life Cycle Cost Tools

Table 1 presents the available LCC tools which are used in practice (Gluch and Baumann 2004). These tools are often classified into a generic and a specific cost model. The specific cost model is the modified generic model which is developed with the system boundary of LCC. A generic model is often developed as a summation of the common cost elements that are related to the product life cycle (Table 1).

## Cross-References

▶ Environmental Impact
▶ Environmental Impact Assessment
▶ Life Cycle Engineering
▶ Sustainability
▶ Sustainability of Machining
▶ Sustainable Manufacturing

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## Life Cycle Cost Analysis

► Life Cycle Cost

## Life Cycle Engineering

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### Definition

A definition for life cycle engineering (LCE) is "engineering activities which include the application of technological and scientific principles to manufacture products with the goal of protecting the environment, conserving resources, encouraging economic progress, keeping in mind social concerns, and the need for sustainability, while optimizing the product life cycle and minimizing pollution and waste."

### Theory and Application

Life cycle engineering was a popular term used before 2000 by those working on engineering that dealt with environmental issues. The foregoing definition is an amalgam of responses by researchers, in 2000, replying to the question, "What is Life Cycle Engineering?" The question was posed because there was no apparent definition, despite there being reference sources such as *Life Cycle Engineering Handbook*, which did not have a definition (Molina and Sanchez 1998). The acronym, LCE, started being used in 1993 (CIRP International Conference on Life Cycle Engineering) for a series of yearly, ongoing conferences sponsored by CIRP (CIRP College International pour la Recherche en Productique). With the advent of increased use of the web, groups using LCE in their descriptions are now common on the Internet, for example, see reference (LCEM).

A CIRP Working Group had been set up in 1993 at the first CIRP-sponsored LCE conference which continues to hold yearly meetings to the present. The first executive consisted of Professor Leo Alting, chair (Danish Technical University), Professor Klaus Feldman, vice-chair (Friedrich-Alexander-Universität at Erlangen), and Professor Jacob Jeswiet, secretary (Queen's University at Kingston). The working group formally became part of CIRP's scientific technical committee (STC A) on assembly and life cycle in 2003. Since that time, members have played an active role in engineering activities concerning the environment.

In the original survey, a typical example of the responses received is given in the following:

> we have not found any firm definition of Life Cycle Engineering, from our point of view Life Cycle Engineering could be defined as follows: Life

**Life Cycle Engineering, Fig. 1** The aegis of LCE (Jeswiet 2003)


Cycle Engineering is a comprehensive engineering approach that, on the one hand, considers not only the actually process phase of the product's life cycle but also all the remaining phases from cradle to grave. On the other hand, environmental topics are integrated into engineering activities and should be self-evident just as economical, technological and market requirements are self-evident. Life Cycle Engineering includes the search for the global optimum between the factors economy, ecology, technology, and market through the entire product life cycle.

LCE is an umbrella for a multitude of work concerned with our physical environment. The definition given at the beginning of this discussion can be illustrated graphically as shown in Fig. 1 (Jeswiet 2003).

From the definition given in the foregoing and as illustrated in Fig. 1, one can see LCE as a system analysis for sustainability and for deceasing environmental impacts.

Simply put, a tenet of LCE is that *design and manufacturing engineers play a critical, central role in deciding the environmental impact of a product*.

## Cross-References

- ▶ Environmental Impact
- ▶ Environmental Impact Assessment
- ▶ EOL Treatment
- ▶ Product Life Cycle Management
- ▶ Resource Efficiency
- ▶ Sustainability
- ▶ Sustainable Manufacturing

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# Life Cycle Impact Assessment

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## Definition

The Life Cycle Impact Assessment (LCIA) is the third phase of the life cycle assessment (LCA) methodology according to the ISO standard for LCA (ISO 14040: 2006; ISO 14044: 2006). The overall LCA methodology and its applications are treated in the entry on "▶ Life Cycle Assessment."

## Theory and Application

An international standard has been developed for the assessment of environmental impacts in LCA as part of the standardization of the methodological foundation (ISO 14040: 2006; ISO 14044: 2006). The standard lays down the structure and principles which are generally acknowledged and followed by all LCIA methodologies today. According to the standard, the impact assessment proceeds through a number of steps:

First the categories of environmental impact to address are defined or – typically – chosen among already defined and developed categories of impact (reference to "▶ Environmental Impact" entry). The selection of impact categories shall be consistent with the goal and scope of the study and reflect a "comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration" (ISO 14044: 2006). Each impact category is represented by an indicator of impact chosen somewhere in the impact pathway that connects the elementary flows of the inventory (reference to "▶ Life Cycle Assessment" entry) and the areas of protection of the LCA – human health, natural environment, and natural resources (reference to "▶ Environmental Impact" entry).

Then the elementary flows from the inventory are assigned to the different categories of impact (reference to "▶ Environmental Impact" entry for default list of impact categories in LCIA). This step is called *classification* of the inventory flows.

Next step is *characterization* where a quantification of the contribution of the elementary flows to the total impact score for the category is calculated using characterization factors. A characterization factor is a quantitative expression of the substance's specific ability to impact on the indicator of the impact category. It is calculated using quantitative models ("characterization models") of the impact pathway that connects the elementary flow to the impact indicator (reference to "▶ Environmental Impact" entry), and it is mainly determined by the inherent properties of the substance since a simplified environment described by generic characteristics ("unit world") is typically assumed. Different types of metrics are used. Sometimes the characterization factor and the impact score are expressed as an equivalent emission of a reference substance for the impact category (for the impact category global warming as kg $CO_2$-equivalents/kg substance), sometimes it is expressed as a direct score for the substance (for the impact category Freshwater ecotoxicity as paf.$m^3$.yr – the potentially affected fraction of species in a certain volume and over a certain duration within the exposed freshwater ecosystem (Rosenbaum et al. 2008)). Characterization is performed as a simple multiplication of the inventory flow and the characterization factor. The resulting indicator scores are summed across elementary flows within the impact category and a total result is obtained (e.g., the total global warming potential for the product system across the whole life cycle expressed as kg $CO_2$-equivalents for the product). The collection of category indicator results for the different impact categories is the *environmental impact profile* of the product.

The third and fourth steps are voluntary and support comparison across impact categories (where the first two steps support comparison and aggregation within the impact categories).

The third step is *Normalization*, where the indicator results from the characterization step are related to a common set of reference information. Frequently, the current level of impact from society within each impact category is chosen as reference information, e.g., expressed as person equivalents, i.e., the annual impact from an average person (Hauschild and Wenzel 1998). Normalization brings all scores on a common scale and expresses them in a common metric, hereby making it easier to relate them to each other and preparing for the likewise voluntary valuation or weighting.

Valuation is the fourth and final step of the LCIA. It is a voluntary step that is normally performed to support conclusion and decision making based on comparative LCAs where there are trade-offs between the results for individual categories of impact (i.e., none of the alternatives is the absolute preference, outperforming the others on all category indicator results). It can be done as a weighting assigning quantitative weights to all category indicators, but it can also be a more qualitative ranking or grouping of the category indicators. It involves subjective choices, and in LCA studies supporting comparative assertions disclosed to the public, the ISO standard does not allow the use of weighting (ISO 14040: 2006; ISO 14044: 2006).

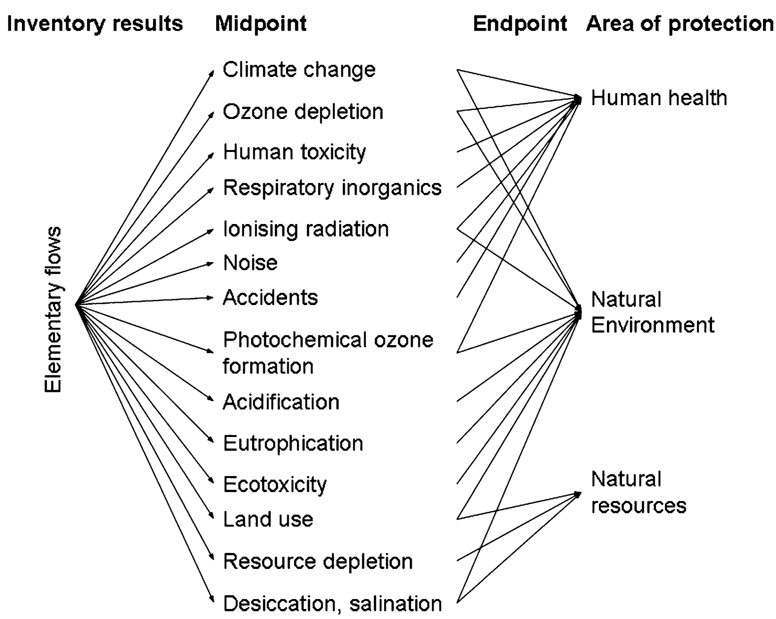
## LCIA Methods

The indicator can be chosen anywhere along the impact pathway from inventory result to the final endpoint, human health, natural environment, or natural resources. Two complementary schools of approaches to LCIA exist in current practice (Hauschild 2005): Midpoint approaches and endpoint approaches, distinguished by the location of the indicators, they choose for modeling the environmental impacts. Endpoint approaches choose their indicator at the endpoint and hence operate with very few impact categories, typically one for each of the areas of protection representing human health damage, damage to the natural environment, and damage to natural resources, respectively.

The midpoint approaches choose indicators at some midpoint in the impact pathway. EC-JRC (2011) argues that the midpoint indicator should ideally be located at that point of the impact pathway where the paths of individual contributors converge, i.e., the earliest point of the impact pathway beyond which there is no distinction in the impact mechanism for the contributing inventory flows. For climate change, the radiative forcing indicator (used for calculation of the GWP) respects this principle. Some of the other impact categories are more heterogeneous, in particular the toxicity-related categories, and then it may not be possible to choose the midpoint following this principle. Here the midpoint is typically chosen as close to the endpoint as it is reasonable considering the trade-off between the wanted reduced uncertainty of interpretation (relative to the endpoint) and the unwanted increased parameter and model uncertainty.

This trade-off is also observed when choosing between midpoint and endpoint methods (Bare et al. 2000; Hauschild 2005). The latter have the strength of aggregating many of the midpoint scores into fewer scores based on environmental






**Life Cycle Impact Assessment, Fig. 1** Midpoint and endpoint impact categories according to the European Commission's ILCD guidelines (adapted from EC-JRC 2010) science modeling making interpretation and decision making easier and less dependent on normalization and weighting. On the other hand, the models applied to calculate the endpoint scores are so uncertain, immature, or deficient for many of the midpoint impact categories that based on the most comprehensive review of LCIA methods performed to date, the current guidelines from the European Commission largely refrain from giving recommendations of LCIA methods at endpoint level (Hauschild et al. 2013; EC-JRC 2011).

Figure 1 shows midpoint and endpoint impact categories and their relation.

A number of LCIA methods have been developed over the last 20 years, both midpoint methods (e.g., *CML 2002* (Guinée et al. 2002), *EDIP97* (Hauschild and Wenzel 1998), *EDIP 2003* (Hauschild and Potting 2005), Swiss Ecoscarcity (Brand et al. 1998) and *TRACI* (Bare et al. 2003)) and endpoint methods (*EPS* (Steen 1999a, b), *Eco-indicator 99* (Goedkoop and Spriensma 2000), or combinations of the two (*LIME* (e.g., Itsubo et al. 2004), *IMPACT 2002+* (Jolliet et al. 2003) and *ReCiPe* (Huijbregts et al. 2016)). EC-JRC 2010 gives a recent and consistent presentation of most of the existing LCIA methods and Hauschild and Huijbregts gives a detailed discussion of LCIA and of all the impact categories that are typically covered in life cycle assessments (Hauschild and Huijbregts 2015).

## Cross References


▶ Environmental Impact
▶ Environmental Impact Assessment
▶ Life Cycle Assessment: Goal and Scope Definition
▶ Life Cycle Assessment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## Life Cycle Management

► Product Life Cycle Management

## Linkage Model

► Mechanism

## Locating

► Positioning

## Logistic Curves

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### Synonyms

Production operating curves

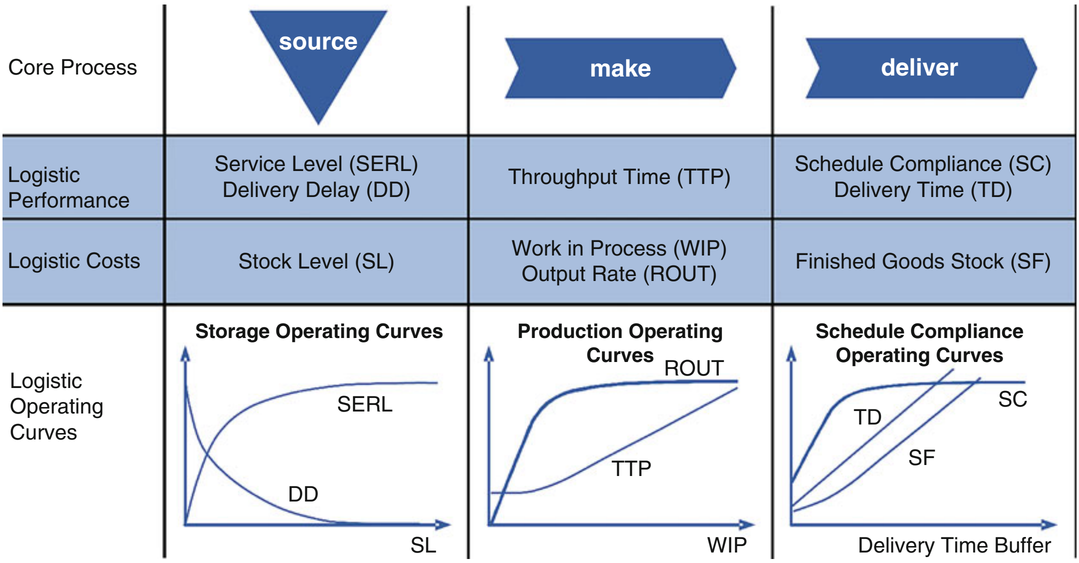
### Definition

Logistic Operating Curves (LOC) qualitatively and quantitatively depict the interaction between logistic objectives in the form of curves.

#### Extended Definition

The company's internal supply chain comprises the core processes: source, make, and deliver (Fig. 1, upper). Each of these core processes focuses on different logistic objectives. These objectives to some extent both contradict and complement one another. A field of tension is created between logistic performance and logistic costs (Fig. 1, middle). Finding an optimum within this field of conflict is impossible for companies. They have to position themselves in the field of tension between the logistic objectives. Among other uses, Logistic Operating Curves provide an excellent tool for accomplishing this (Fig. 1, lower).

Usually, the actual procurement process is decoupled from the production via a warehouse of raw and/or semifinished goods. In order to guarantee a strong logistic performance, this store is supposed to ensure a high service level with a minimum delivery delay while at the same time maintaining as little stock as possible in order to keep the logistic costs down. As the Storage Operating Curves (Lutz 2002; Glässner 1995; Nyhuis 1996) show, these targets are to some extent contradictory. In this case, the logistic objective "stock level" is also the controlled




**Logistic Curves, Fig. 1** Core processes, objectives, and exemplary Logistic Operating Curves

variable which can, for example, be set via the reorder point in the ERP system. When the stock level is high, a high service level and minimum delivery delay are to be expected since all of the stored parts are generally available. As the average stock level decreases, fewer of the demands on the store can be met. As a result, the service level sinks and the mean delivery delay increases.

In the field of production, the logistic objectives “throughput time” and “schedule reliability” (logistic performance) as well as “utilization” and “WIP” (logistic costs) are of key importance. The Production Operating Curves show that when there is a high WIP level, the output rate and with that the utilization of a workstation is for the most part independent of the WIP. Should the WIP, however, fall below a certain value, utilization problems arise due to a temporary lack of work. In comparison, the throughput time grows for the most part proportional to the increasing WIP. Short throughput times as a result of low WIP are also generally related to minimal variance. From the perspective of the subsequent production areas, the greater planning certainty arising from this causes greater schedule reliability (Nyhuis and Wiendahl 2009).

If we assume a make-to-stock production when discussing the distribution core process, the Storage Operating Curves, already outlined above in regard to procurement, can be applied. In comparison, with a make-to-order production, the logistic objectives from the perspective of performance are high schedule compliance and short delivery times, whereas from the cost perspective the objective is a small store of finished orders, that is, completed orders should only wait briefly before being shipped to the customer. In this case, the controlled variable is the delivery time buffer. If a larger delivery time buffer is selected, the majority of promised delivery dates can be met. The delivery time buffer also directly impacts the delivery time extending it by the same amount. Moreover, a very large number of orders will be completed before the actual planned delivery date, subsequently giving rise to a bigger store of finished products. As can be seen in the Schedule Compliance Operating Curves, with shorter delivery time buffers, the delivery times and the stores of finished products also decrease. When the static distribution of the lateness is constant in the preceding production area, the schedule compliance decreases (Schmidt et al. 2013).

## Theory and Application

The Logistic Operating Curves are impact models derived either from deductive or deductive/experimental modeling. They depict interactions between logistic objectives. Their mathematically calculated progression is dependent on various parameters. If the parameters change, the shape of the operating curve adjusts. This allows logistic measures to be evaluated with the aid of the Logistic Operating Curves.

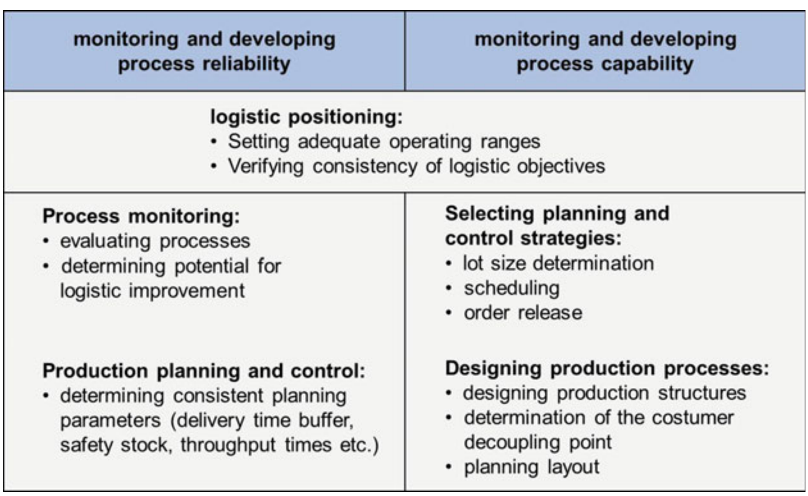
The shape of the Storage Operating Curves is dependent on both the fluctuating demands on the store output side as well as the replenishment time and the quality of the supplier's delivery (i.e., with regard to quantity and due date). For example, the greater the supplier's due date reliability, the steeper is the slope of the Service Level Operating Curve. This means that, compared to initial state, a lower stock level is required to ensure a desired service level.

A number of parameters, for example, technical disruptions, load variance, capacity flexibility, or lot sizes, among others, are taken into consideration by the Production Operating Curves. Logistic measures that impact these parameters can thus be evaluated based on the changes in the operating curves.

The Schedule Compliance Operating Curves are determined by the distribution of the output lateness of the preceding production stage. Logistic measures such as those for improving the due date reliability or for narrowing the distribution of the due date reliability directly impact the shape of the Schedule Compliance Operating Curves. Thus with less variance in the lateness, a shorter delivery time buffer is occasionally necessary in order to realize a defined target due date compliance.

A variety of possible applications for the Logistic Operating Curves arise from the connections demonstrated here. These are summarized in Fig. 2. Since the Logistic Operating Curves describe the correlations between the logistic objectives and the possibility of influencing them, they represent an ideal foundation for increasing and monitoring the certainty and capability of logistic processes in an enterprise. The Logistic Operating Curves can thus be drawn upon for evaluating processes within the frame of monitoring logistic process in enterprises particularly in the production as well as for deriving potential. They show, for example, which throughput times and WIP level can be achieved with the existing structural conditions without having to expect noteworthy breaks in the material flow or a loss of output. When applying them within the frame of production planning and control, the system parameters such as the delivery time buffer, safety stock, or throughput times can be derived and set in agreement with the goals. Depicting the logistic objectives in a diagram also makes it possible to determine which of them should be weighted the most depending on the current operating and/or market situation as well






**Logistic Curves, Fig. 2** Application areas for Logistic Operating Curves as depending on the system specific conditions. At the same time, it can be shown how the changes in the parameters impact the logistical quality indicators.

Should it turn out that the set target values are not attainable without supporting measures, the operating curves can be drawn upon according to the possibilities introduced here for reinforcing and evaluating planning activities and thus work as an aid in stabilizing the process certainty. Thus alternative, implementable planning and control strategies can be evaluated and selected according to logistic criteria. Logistic Operating Curves can also be directly integrated into planning and control methods (e.g., lot sizing, scheduling, order release). Moreover, applying them provides continual, method-based support for orienting the planning and control on the logistic objectives. When designing production processes, Logistic Operating Curves can be implemented as an aid to resolving diverse problems. They can, for example, assist in evaluating alternative manufacturing principles (in view of logistics) or new logistic concepts, determining the customer decoupling point or planning the layout. The basis for all of the mentioned applications is a Logistic Positioning which provides the target values and thus also represents a link between all of the individual functions.

## Cross-References

- ▶ Changeable Manufacturing
- ▶ Factory
- ▶ Logistics
- ▶ Machine Tool
- ▶ Manufacturing
- ▶ Manufacturing System
- ▶ Production
- ▶ System

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# Logistics


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## Synonyms

Flow of materials; Material transfer; Supply chain; Transportation planning

## Definition

Logistics is the management of materials' flow from one location to another. Logistics involves the integration of information, transportation, inventory, warehousing, material handling, and packaging.

### Extended Definition

Logistics is concerned with managing transportation, warehousing, and inventory stocking activities. According to the Council of Logistics Management Professionals (CSCMP 2011), *it is* *the process of planning, implementing, and controlling the efficient, effective flow and storage of goods, services, and related information from point of origin to point of consumption for the purpose of conforming to customer requirements*. Transportation planning is a vast field that involves complex decisions about transportation modes, carriers, vehicle scheduling and routing, and many other activities that serve to move products through the company's supply chain (Shapiro 2001). The fundamental goal of logistics can thus be formulated as the pursuance of greater delivery capability and reliability with the lowest possible logistic and production costs (Nyhuis and Wiendahl 2009). Logistics plays a key role in every supply chain because products are rarely produced and consumed at the same location.

## Theory and Application

### Introduction

There are two main challenges that make logistics (or supply chain) management challenging (Simchi-Levi et al. 2005):

1. The design and operation of a logistics system so that the costs are minimized in a system-wide manner and at the same time system-wide service levels are maintained.
2. Uncertainty – customer demand can never be forecast exactly, transportation times will never be certain, and machines and vehicles will occasionally break down.

Some typical examples of logistics management are the following (Simchi-Levi et al. 2005):

- ***Network configuration***: The goal is to choose a set of facility locations and capacities, to determine production levels for each product at each plant and to set transportation flows between facilities, either from plant to warehouse or warehouse to retailer, in such a way that total production, inventory, and transportation costs are minimized and various service level requirements are satisfied.
- ***Production planning***: The objective is to satisfy demand for the product in each period and to minimize the total production and inventory costs over the fixed horizon. Obviously, this problem becomes more difficult as the number of products and variants manufactured increases.
- ***Inventory control and pricing optimization***: Consider a retailer that maintains an inventory of a particular product. The retailer's objective is to find an inventory policy and a pricing strategy maximizing expected profit over the finite, or infinite, time horizon.
- ***Integration of production, inventory, and transportation decisions***: The timing and routing of shipments need to be coordinated so as to minimize system-wide costs, including production, inventory, transportation, and shortage costs, by taking advantage of economies of scale offered by the carriers.
- ***Vehicle fleet management and vehicle routing***: Here the objectives are to minimize the number of vehicles used while reducing the total distance traveled. The latter objective of finding the minimal length route, in either time or distance, is an example of a traveling salesman problem (TSP).

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Mourtzis (2016) discussed the main challenges for the manufacturing networks imposed by the need for customized products design and manufacturing. Extending the earlier work of Simchi-Levi et al. (2005), the main challenges identified in Mourtzis (2016) are (a) supplier selection, (b) supply chain coordination, (c) initial manufacturing network configuration, (d) inventory management/capacity planning/lot sizing, (e) logistics management, (f) simulation and ICT support systems for manufacturing network life cycle, (g) simulation for manufacturing network design, (h) enterprise resource planning, (i) customer relationship management, and (k) cloud computing and manufacturing.

### Methods and Tools

Economic systems are generally modeled mathematically. The methods and tools for the design and operation of production systems may fall into three broad categories: *operations research*, *artificial intelligence*, and *simulation* (Chryssolouris 2006). The information on these three categories provided below is based on the work of Chryssolouris (2006).

### Operations Research

***Mathematical programming*** is a family of techniques for optimizing (minimizing or maximizing) a given algebraic objective function of a number of decision variables. The decision variables may either be independent of one another or they may be related through constraints. Mathematical programming solves problems of the form

$$\begin{gathered}\text{Minimize or maximize } \mathrm{f}(\mathrm{x}_1, \mathrm{x}_2, \ldots, \mathrm{x}_n)\\ \text{Subject to the constraints :}\\ g_1(x_1, x_2, \ldots, x_n) \Diamond b_1\\ g_2(x_1, x_2, \ldots, x_n) \Diamond b_2\\ \ldots\\ g_m(x_1, x_2, \ldots, x_n) \Diamond b_m\end{gathered}$$

where the symbol $\Diamond$ stands for one of the relations $\leq$, $=$, or $\geq$ (not necessarily the same relation for each constraint). A mathematical program is called a *linear program* if the objective function $f(x_1, x_2, \ldots, x_n)$ and each constraint function $g_i(x_1, x_2, \ldots, x_n)$ are linear in their arguments. If there is an additional constraint that the decision variables $x_1, x_2, \ldots, x_n$ should be integers, then an integer program is a *linear* one.

***Dynamic programming*** is a method for solving problems that can be viewed as *multistage decision processes*. A multistage decision process is a process that can be separated into a number of sequential steps, or stages, which may be completed in one or more ways. The options for completing the stages are called *decisions*. A *policy* is a sequence of decisions, one for each stage of the process. The condition of the process at a given stage is called the *state* at that stage; each decision effects a transition from the current state to a state associated with the next stage. Many multistage decision processes have *returns* (costs or benefits) associated with each decision, and these returns may vary with both the stage and state of the process. Bellman (1954) used dynamic programming to model the inventory optimization problem as multistage processes composed of a sequence of operations.

***Queuing theory*** models are used for describing the relationships between logistic parameters. Queuing or waiting line models consists of customers arriving at a service facility, then waiting in a line (queue) if all servers are busy, eventually receiving service, and finally departing from the facility. Queuing systems are characterized by five components: the arrival pattern of customers, the service pattern, the number of servers, the capacity of the facility to hold customers, and the order in which customers are served. They are mainly used to dimension the size of bottlenecks which can occur whenever an object of any sort arrives regulated or randomly at one or more servers and are served with irregular or fixed processing times. By using mathematical approaches and given information known about the input (in particular the average arrival and completion/service rate of the objects on the operating system), the events that take place during the actual processing should become theoretically comprehensible and therefore predictable.

### Artificial Intelligence

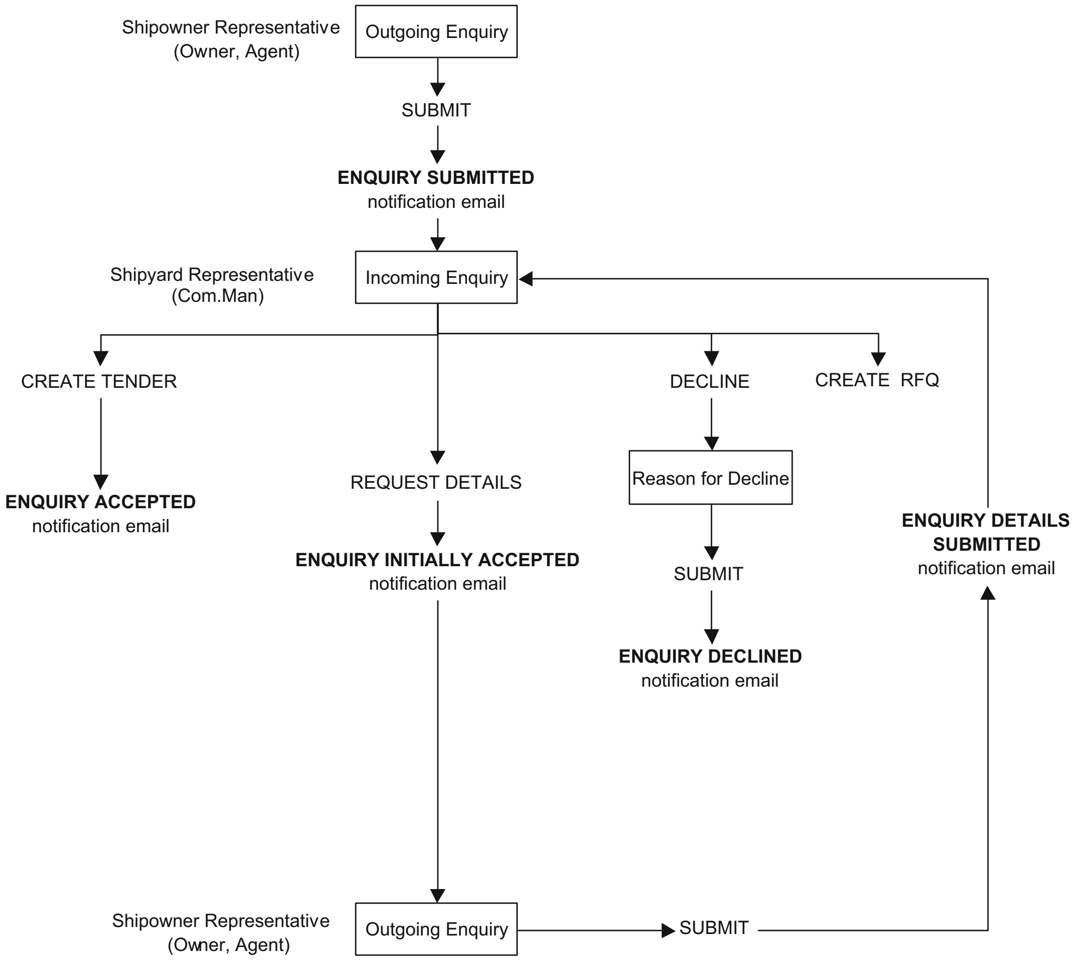
The field of artificial intelligence may be defined as the study of ideas that enable computers to be intelligent. Its main goals are to make computers more useful and to understand the principles that make intelligence possible. Since the first of these goals is the most relevant to designing of logistics systems, an artificial intelligence tool, namely, *heuristics*, will be shortly described below. The body of heuristics or intuitively "reasonable" rules, which the designer can use to establish a path (hopefully short) through the design space, is called *search* (Chryssolouris 2006). In recent years, several powerful heuristics have been proposed for the vehicle routing problem and its variants, based on local search, population search, and learning mechanisms principles (Langevin and Riopel 2005). Local search includes descent algorithms, simulated annealing, deterministic annealing, and tabu search. The two best known types of population search heuristics are evolutionary algorithms and adaptive memory procedures. Examples of learning mechanisms are neural networks and ant algorithms. Heuristics remains a reliable approach for the solution of practical instances of hard combinatorial problem such as the vehicle routing problem (Langevin and Riopel 2005). Mourtzis and Doukas (2015) presented a research work that describes the modeling and solving of supply chain configuration problems using the simulated annealing and tabu search methods.

### Computer Simulation

Today, simulation is a widespread technique for researching, designing, and optimizing complex systems. Conceptually, the inputs of a computer simulator are decision variables, which specify the design (e.g., number of vehicles, routings), the workload (e.g., arrivals of raw materials over time), the operational policy (e.g., "first come, first served"), and others. The simulator assembles these data into a *model* of the system, including the rules as to how the components of the system interact with each other. The user of the simulator specifies the initial *state*. Starting from this initial state, the simulator follows the operation of the model over time, tracking *events* such as parts' movement and machine and vehicle breakdowns over time. At the conclusion of the simulation, the output provided by the simulator is a set of statistical performance measures (e.g., the average number of parts delivered over time) by which the chain may be evaluated.

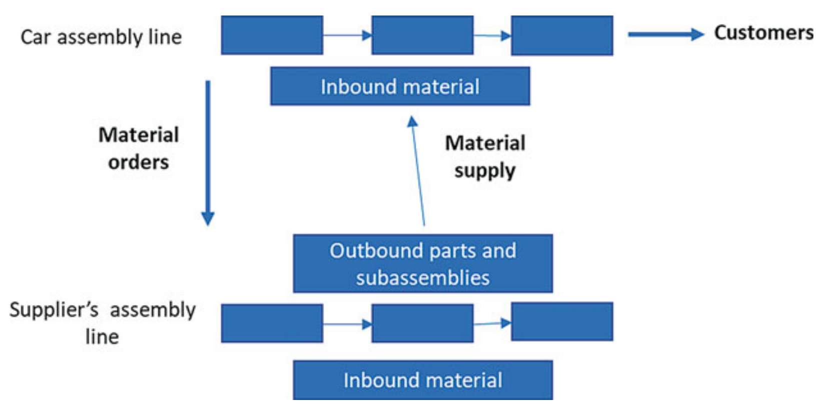
### Logistics and Information Technology

Logistics deals with the flow and storage of goods and related information. Previously viewed as a clerical function involving adversarial relationships between suppliers, customers, and transportation providers, logistics is emerging as a key source of competitive advantage and a leading reason for the emergence of interorganizational systems (Lewis and Talalayevsky 1997). It is common practice to implement computer-based environments in order to facilitate automated communication among the actors involved in the logistics. Value chain integration uses Internet technology to improve communication and collaboration among all parties within a supply chain (Papazoglou et al. 2000). According to Lancioni et al. (2003), the Internet fosters the integration of business processes across the network by facilitating the information flows that are necessary to coordinate business activities. The requirement from a value chain integration software environment is to be able to bring all the related partners together. Each partner uses its own system that supports its business. As a result, a large number of heterogeneous software systems must exchange data related to the business process. Because each system uses a specific data storage mechanism, direct exchange of data among these systems is not possible. This is the main reason for the slow execution of the business process and the reduced performance of the entire supply chain. In order to step up the computer-based data exchange within the supply chain, we should reduce the effort required to accomplish the communication among the different software systems, enabling the easy and fast flow of information among the partners. In Chryssolouris et al. (2004), an XML, three-tier, web-based approach is presented for supporting the communication of different partners and enables information flow within the chain of the ship repair industry. Moreover, it is difficult to monitor and control the efficiency and quality of enterprise logistics services due to the large amount of information generated across various logistics activities and participants. In order to tackle this problem, there is a growing trend to adopt an emerging technology called radio-frequency identification (RFID) in logistics and supply chain management so as to improve operational efficiency for generating a profit eventually. The areas of use of this technology include shipping and port operations, warehouse operations, and product tracking (Chow et al. 2007). In Papakostas et al. (2015), the concept of Dynamic Manufacturing Network (DMN) is proposed as a solution to rapidly and

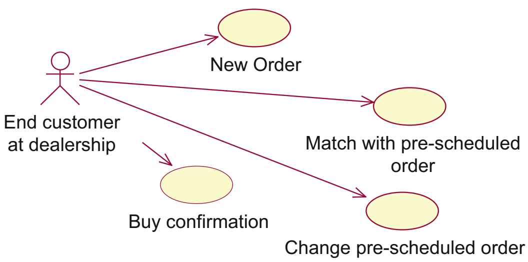



**Logistics, Fig. 1** Business process model of an ship repair inquiry

**Logistics, Fig. 2** Structure of a typical supply chain in automotive industry



efficiently designing and operating a new manufacturing network or to reconfiguring an existing one, in order for specific objectives in each situation to be accomplished. DMN approach was presented for solving the problem of supplier selection in the furniture manufacturing industry.

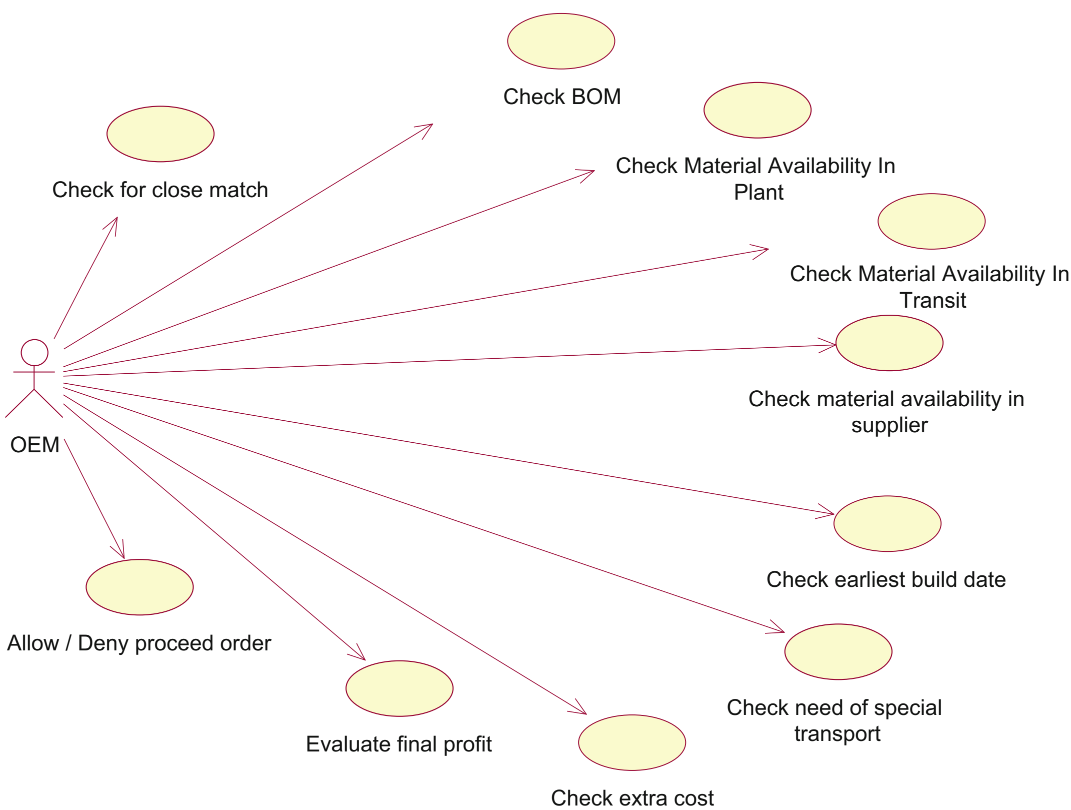



**Logistics, Fig. 3** Dealer use case

## Applications

### Ship Repair Industry

In order for the ship repair process to be efficient, the data exchange among the involved stakeholders should take place in a minimum time and effort manner (Makris et al. 2008). A significant number of stakeholders participate in this process such as the shipowner, the emergency response company, the classification society, the emergency response company, the hull insurer, and the shipyard. The ship repair process typically starts with the inquiry process performed by the shipowner or his representative, the tendering process performed by the shipyard, the contracting process, the subcontracting process, and finally the invoicing process. An example of such a process is the inquiry control process shown in the following Fig. 1.




**Logistics, Fig. 4** OEM use case

Automotive Industry

In Makris et al. (2011), an Internet-based supply chain control logic, where supply chain partners provide real-time or near real-time information, regarding the availability of parts needed for the production of highly customizable vehicles, is presented. The logistics plan that is generated ensures the supply of the right part at the right time at a rather reasonable cost, thus eliminating the quality defects of the product.

A simplified structure of the automotive supply chain is shown in Fig. 2. An automotive company's supply chain comprises geographically dispersed facilities, where raw materials, intermediate products, or finished products are acquired, transformed, stored, or sold, and the transportation links that connect facilities along which the products flow (Shapiro 2001; Mourtzis et al. 2008).

The supply chain is rather complex since it involves the interaction of several companies, which in several modeling efforts are called actors. Different actors performed different functions in the business process. Example of such business functions can be seen in the following use case diagrams, according to the notation of the Unified Modeling Language.

Figure 3 presents the dealer functions in a use case diagram. The functions of the end customer at the dealership are the place of a new order, the match with a prescheduled order, the change of a prescheduled order, and buy confirmation.

Figure 4 presents the OEM functions in a use case diagram. Regarding the material availability, OEM checks for availability in supplier, in transit and in plant. Also, it checks for a close match, defines the material needed, checks the earliest build date and the need of special transport, checks the extra costs, evaluates the final profit, and allows/denies the proceed of the order.

Such business models rely in the core of business process control software systems, which are in charge of facilitating the interaction of the different actors and thus ensuring a smooth process of handling the logistics within the supply chain.

## Cross-References

▶ Material Flow

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## Loose Abrasive Machining

► Lapping

## Low Temperature Silver Die-Attach

► Silver Sintering

## Low-Temperature Solid-Liquid Interdiffusion Bonding

► Diffusion Soldering