L

Lapping

Eckart Uhlmann
Fraunhofer Institute for Production Systems and Design Technology, Berlin, Germany
Institute for Machine Tools and Factory Management, Technische Universität Berlin, Berlin, Germany

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

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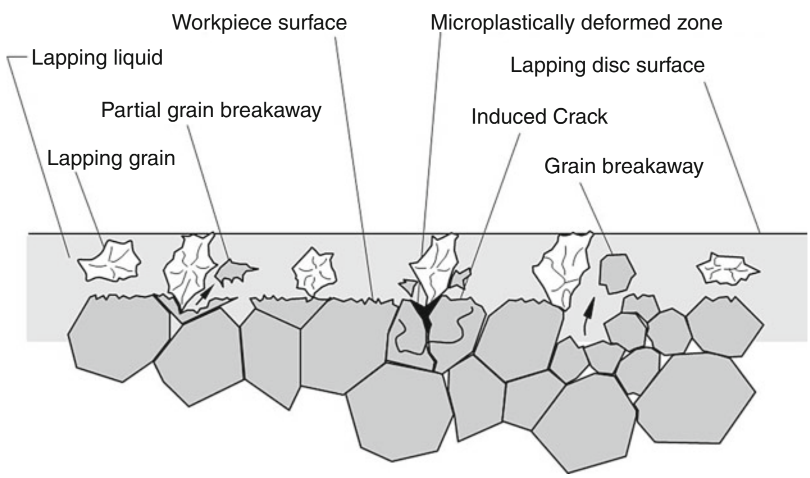
rather appear. When processing brittle hard materials, micro cracks are induced and crack systems occur, which lead to breakaways of particles (Fig. 1). The structure of the workpiece surface is significantly influenced by the applied lapping pressure, lapping grain size, and the relative velocity (Spur et al. 1989).

Lapping, Table 1 Advantages and disadvantages of lapping

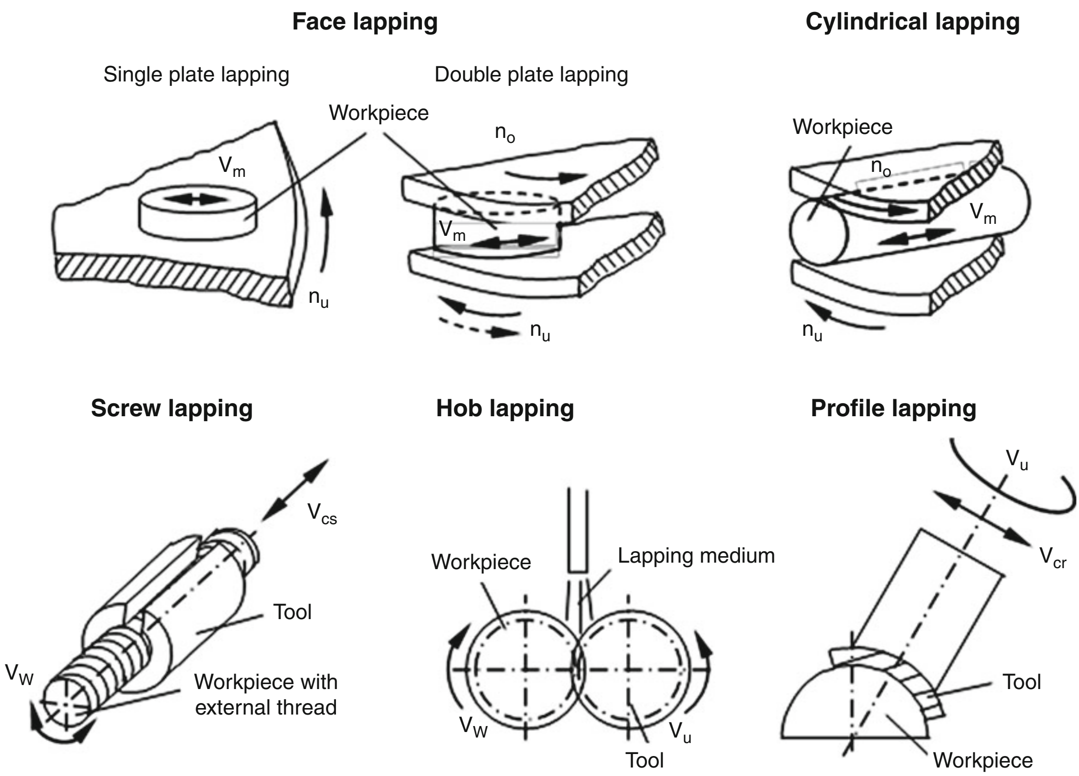
Advantages	Disadvantages
Possibility of processing almost every material and part size	Disposal of the lapping sludge as special waste
Short changeover time as well as low costs for workpiece holders	Comparatively low removal rates at high wastage of grain
Processing several workpieces in one operation 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	

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 noneffective 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



Lapping, Fig. 1 Material removal caused by grains



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

rate increases (rough lapping). To accomplish better surface qualities, it is common to run the machine 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

Eduardo Weingärtner[1], Konrad Wegener[1] and Claus Dold[2]
[1]Institute of Machine Tools and Manufacturing (IWF), Swiss Federal Institute of Technology (ETH), Zürich, Switzerland
[2]Inspire AG, Swiss Federal Institute of Technology (ETH), Zürich, Switzerland

Synonyms

Sublimation; Vaporization

Definition

Laser ablation describes a material removal mechanism in which 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

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

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 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)

$$I(z) = (1 - R)I_0 e^{-\mu z}$$

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

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

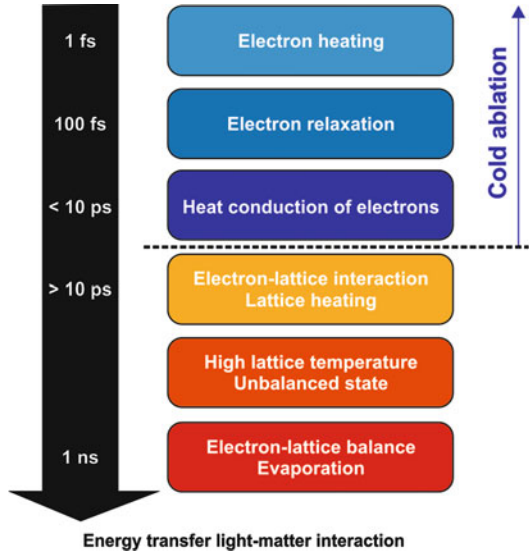
The absorption of laser radiation in opaque materials can be calculated as follows:

$$A = 1 - R$$

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

$$n_c = n - ik$$

where A is the absorption, R 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 the 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



Laser Ablation, Fig. 1 Pulsewidth ablation regimes in pulsed laser ablation in the case of metals

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.

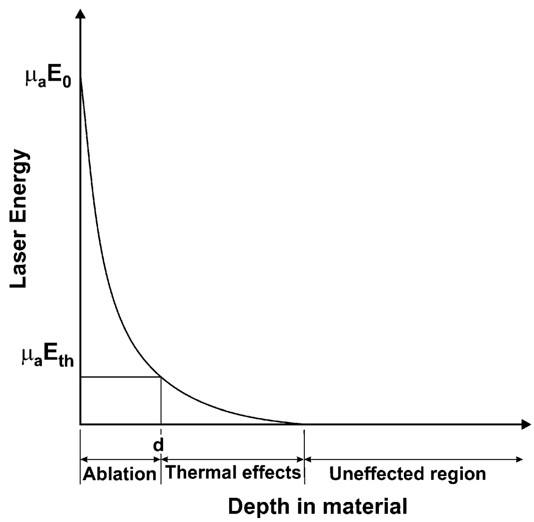
For matter with absorption bands in the deep ultraviolet, moderate intensities will not lead to ablation by a one-photon process. Within this mechanism, two or more photons in the visible and infrared region are absorbed at the same time, which has the same effect as a deep ultraviolet photon with an 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

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

where κ is the thermal conductivity, c_p the heat capacity, ρ the mass density, and t_p represents the pulse duration. Dahotre et al. describe the ablation model as a "blowoff" model which assumes that material is removed if an ablation threshold $\mu_a E_{th}$ is reached; here μ_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 material is irradiated with incident laser energy E_0.

In the case for femtosecond pulsewidths, a two-temperature model is used. Here,



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

decoupling of the effects of the electron and the phonon system takes place. The two primary equations are

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

$$C_p \frac{dT_p}{dt} = \mu(T_e - T_p)$$

where C_e and C_p are the heat capacities of the electron and the phonon system, κ_e is heat conductivity of the electron system, S represents the incident optical energy, μ 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

Jan Düsing, Sirko Pamin and André Neumeister
Laser Zentrum Hannover e.V., Hannover, Germany

Synonyms

Laser beam processing

Definition

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

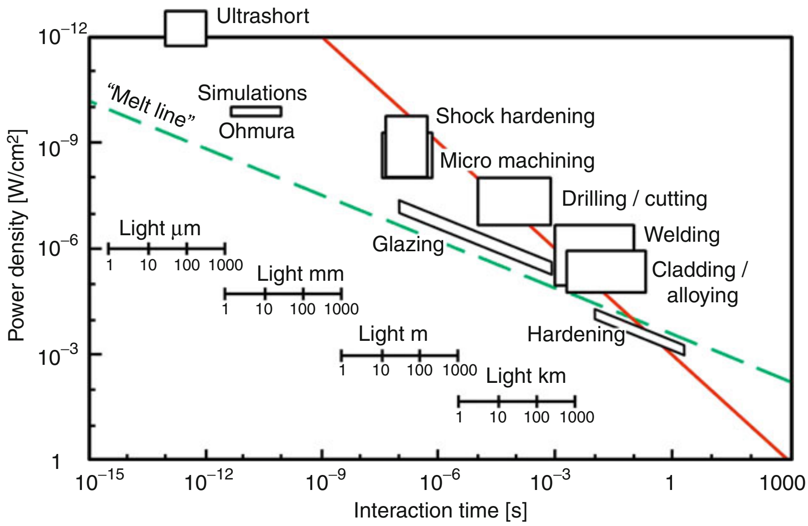
Theory and Application

Introduction

Laser beams are highly directed, coherent, and monochromatic waves of electromagnetic radiation in the spectral range between ≈ 100 nm (far UV) up to 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 field 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.



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)

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 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. 2–4, Tables 1 and 2).

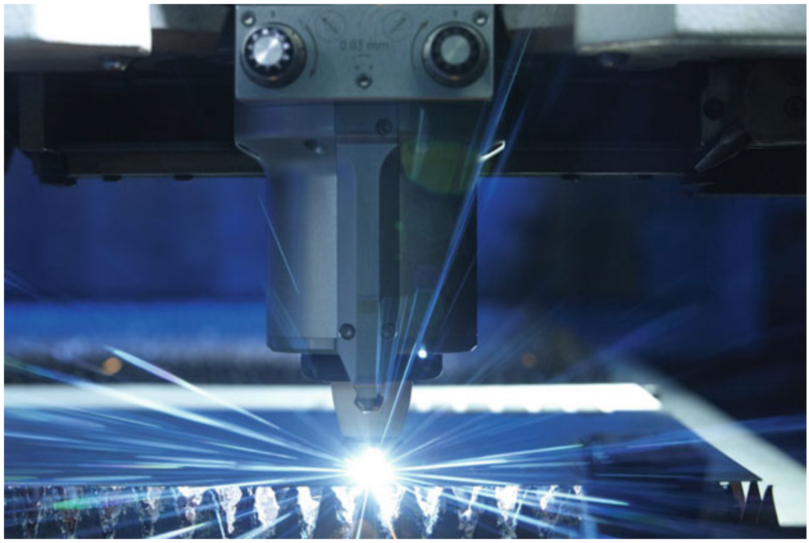
Joining

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.

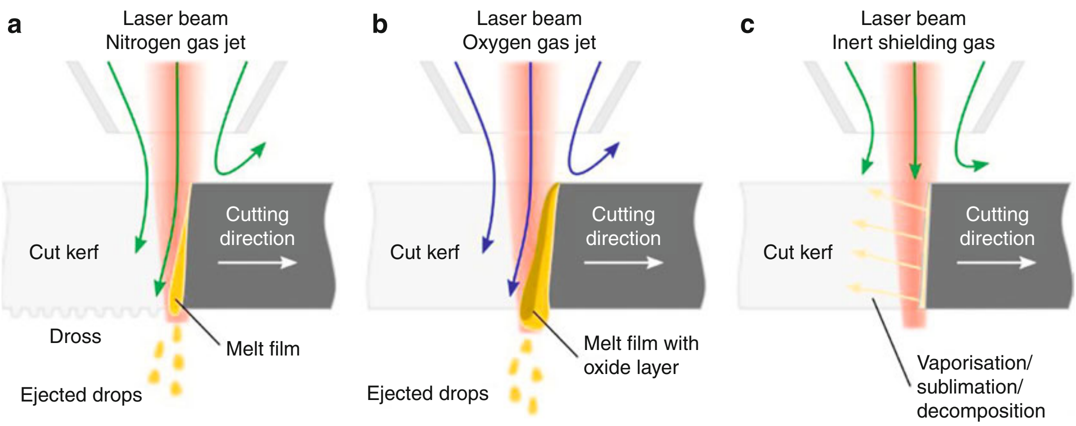
Drilling and Ablation

With laser beams, materials can be precisely removed in a noncontact and reproducible manner. 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).

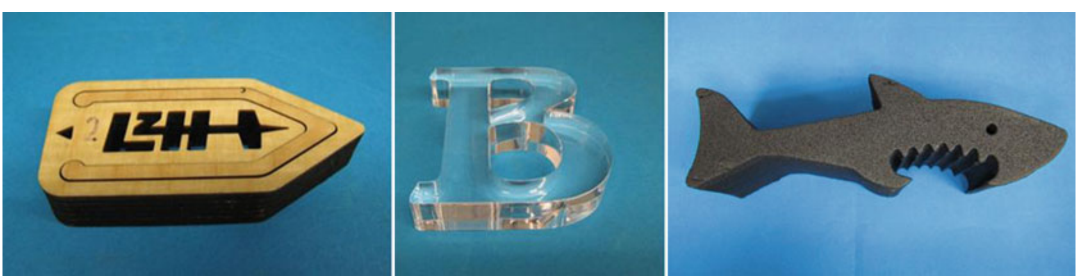
Laser beam drilling enables processing of small holes with high aspect ratios, high angles of incidence, or with undercuts (Dahotre and Harimkar 2008). It can be an alternative process to mechanical drilling or EDM drilling, especially if holes must be formed under difficult conditions (hardened materials,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



Laser Beam Machining, Fig. 2 Laser cutting of thin sheet



Laser Beam Machining, Fig. 3 Laser cutting techniques: (**a**) fusion cutting, (**b**) oxygen cutting, (**c**) sublimation cutting (Kaplan 2002)



Laser Beam Machining, Fig. 4 Examples of cut materials: wood, PMMA, and foam (from *left* to *right*)

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		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		Cutting width (different metals/alloys) <20 µm

percussion, and trepanning drilling (Fig. 5a–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 to 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 ▶ laser ablation processes, exemplary: micromachining, thin film patterning, cleaning, scribing, or as a surgical tool. For laser ablation processes laser beams with short pulses (ns to µs regime) or ultrashort pulses (fs or ps regime) are often preferred since heat affected zones can be reduced (Meijer et al. 2002). Reducing the pulse duration enables high precision machining even of materials with high heat conductivity, e.g., metals. It enables high precision machining with resolution down into the sub-µm regime.

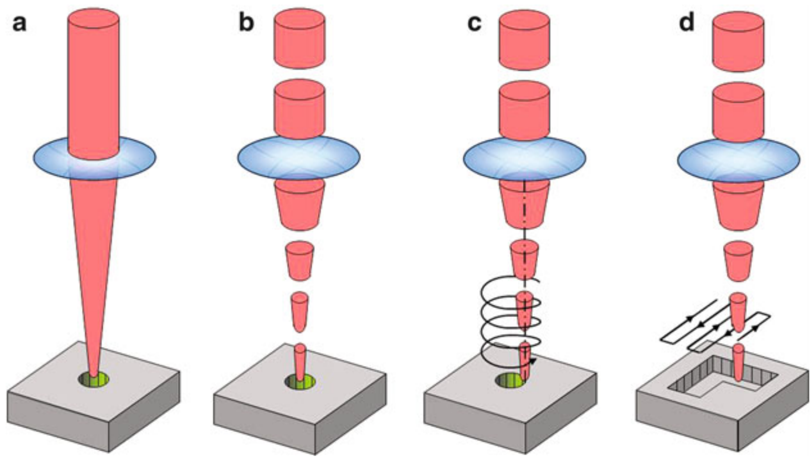
In industrial applications, laser machining approaches are generally classified in imaging and writing techniques. The imaging techniques are based on projection of a mask onto the surface of a workpiece. The process resolution of the imaging system is diffraction limited and can be estimated by the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

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

where λ 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. 5d). 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 nanomachining have been



Laser Beam Machining, Fig. 5 Process approaches for single pulse, percussion, and trepanning drilling (**a–c**) as well as machining (**d**) with focused laser beams

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

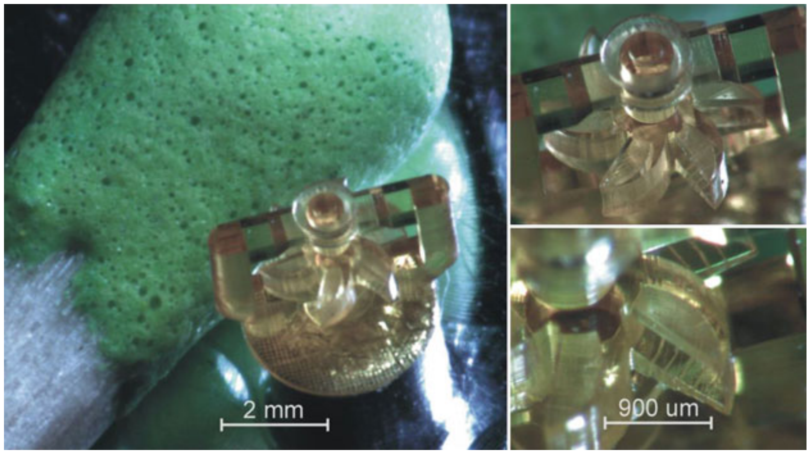
Due to its locally well-defined and concentrated energy input, laser radiation is suitable for surface treatment applications of small and complex part geometries with almost no dilation. In contrast to other methods, laser surface treatment is also characterized by high cooling rates. *Laser hardening* 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,

Laser Beam Machining, Fig. 6 Micromechanical components with moveable parts generated by laser-based layer manufacturing (microstereolithography)



research and development has 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 proven (Fig. 6).

Cross-References

▶ Additive Manufacturing Technologies
▶ Laser Ablation
▶ Laser Welding
▶ Pulse
▶ Rapid Tooling

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Laser Beam Processing

▶ Laser Beam Machining

Laser Beam Welding

▶ Laser Welding

Laser Pulse

▶ Pulse

Laser Welding

Michael Zaeh
TU München, iwb - Institut für Werkzeugmaschinen und Betriebswissenschaften, Munich, Germany

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 Stimulation 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 *micro processing*. 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 (Deutsches Institut für Normung e.V. 2008). 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.

$$BPP = \frac{d_{\sigma 0} \cdot \Theta_{\sigma}}{4} in\, 1 \cdot \mathrm{mm} \cdot \mathrm{mrad} \qquad (1)$$

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).

$$I = \frac{dP}{dA} in\, 1 \cdot \frac{W}{m^2} \qquad (2)$$

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).

$$V = \frac{h}{b} \qquad (3)$$

Theory

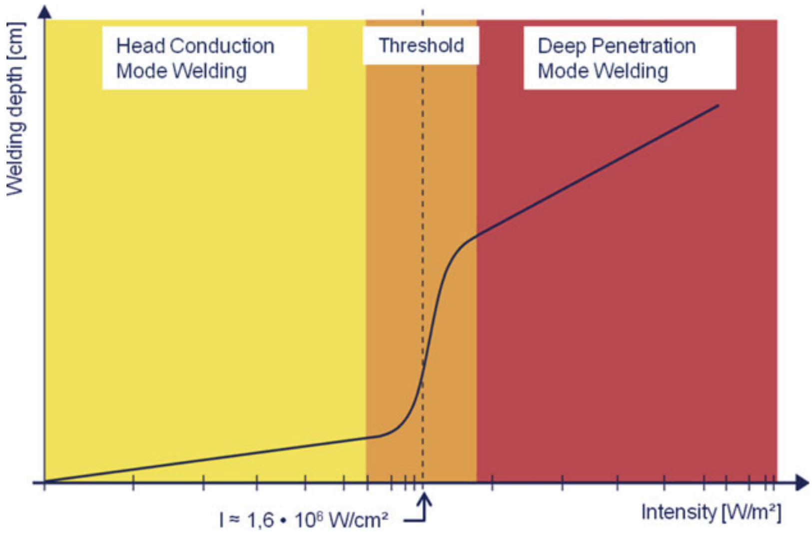
Heating and Surface Melting

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

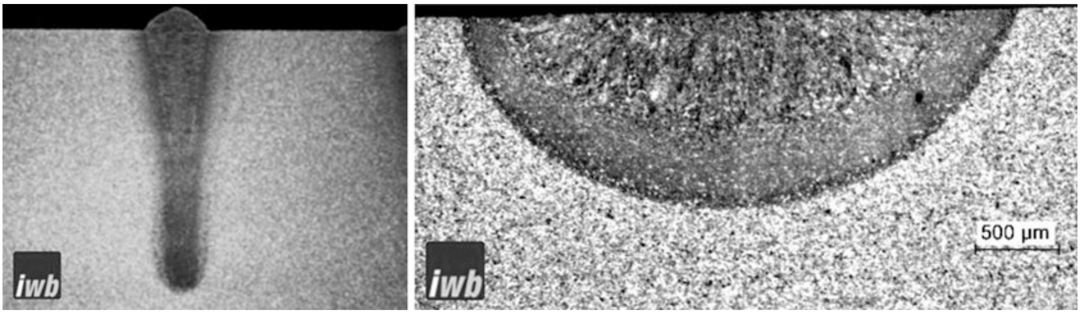
Heat Conduction Mode Welding Heat conduction mode welding describes a family of effects in which the laser beam is adjusted to give a power irradiance of $I \approx 1 \cdot 10^4 \frac{\mathrm{W}}{\mathrm{cm}^2}$ which is used to create a joint without significant

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



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 Fig. 1 describes, heat conduction mode welding produces low welding depths ($I \geq 1 \cdot 10^6 \frac{W}{m^2}$ mm) 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. 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 steal), 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. 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



Laser Welding, Fig. 2 (*Left*) cross section of a heat conduction mode welded seam; (*right*) cross section of a deep penetration welded seam

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 is 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 centerline 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 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 and Brandenburg 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 and 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 (Krastl 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. In the BMW three series Touring model, the welding of the roof body shell with the side frame was the first application. Also the welding of aluminum, e.g., in the five and seven series from BMW was established (Hornig 2002).

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

Layered Manufacturing

▶ Additive Manufacturing Technologies

Layout Planning

▶ Facility Planning

LBW

▶ Laser Welding

Learning Organization

Engelbert Westkämper
Fraunhofer-Institute IPA, University Stuttgart Graduate School for advanced Manufacturing Engineering, Stuttgart, Germany

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 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.

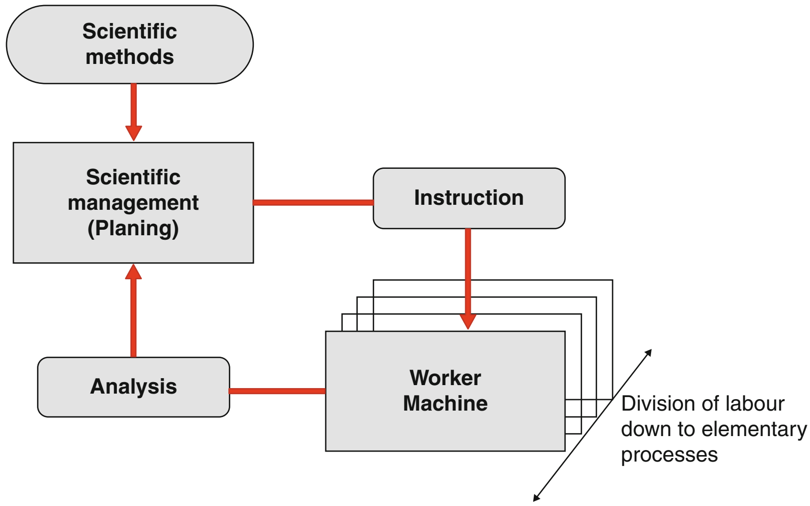
Multilevel System of Manufacturing

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:

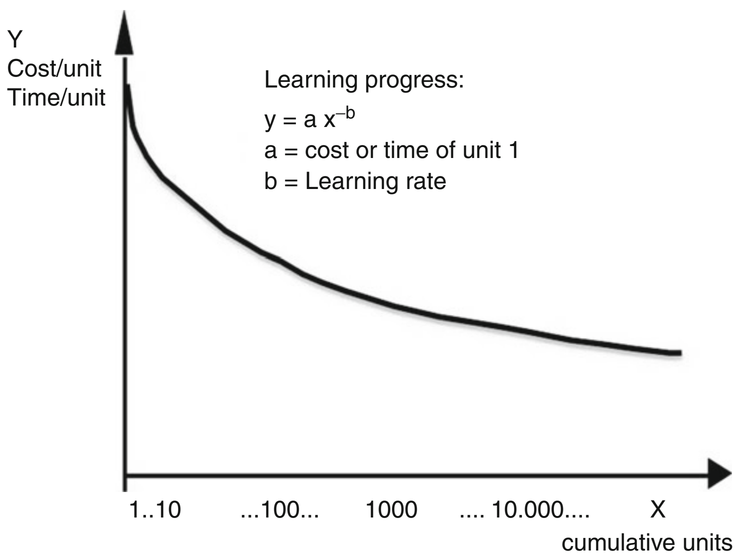
- Time (from µsec, minutes, hours, days, month, years)
- Space, locations, etc.
- Material resource
- Humans (social elements)
- Information
- Elements of the system

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.)



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



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

- 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.

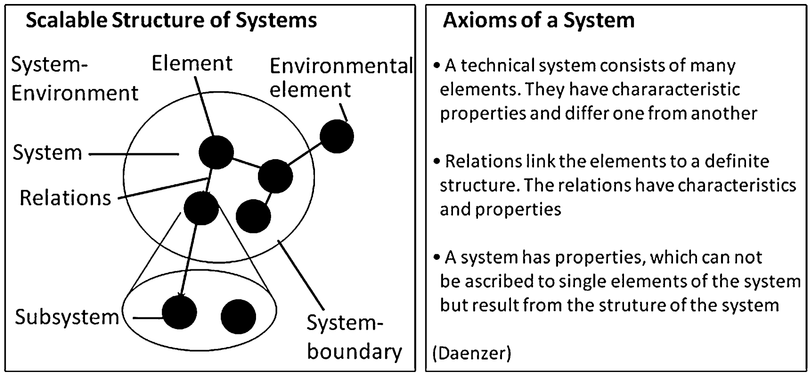
Learning Organization in Multilevel Systems of Manufacturing

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.

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



Key Applications

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

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

Cross-References

► Flexible Manufacturing System
► Manufacturing System

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Life Cycle Cost

Sami Kara
School of Mechanical & Manufacturing Engineering, The University of New South Wales, Sydney, NSW, Australia

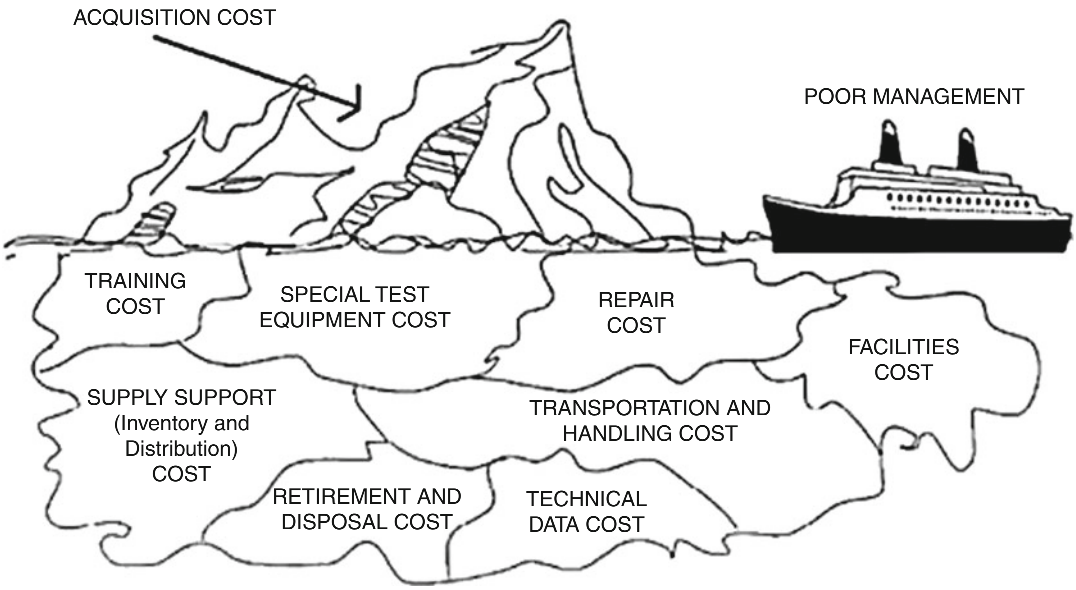
Synonyms

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 Cost, Fig. 1 An iceberg analogy for the total cost visibility (HM Treasury 1992)

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), 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 as illustrated in Fig. 1.

Theory and Application

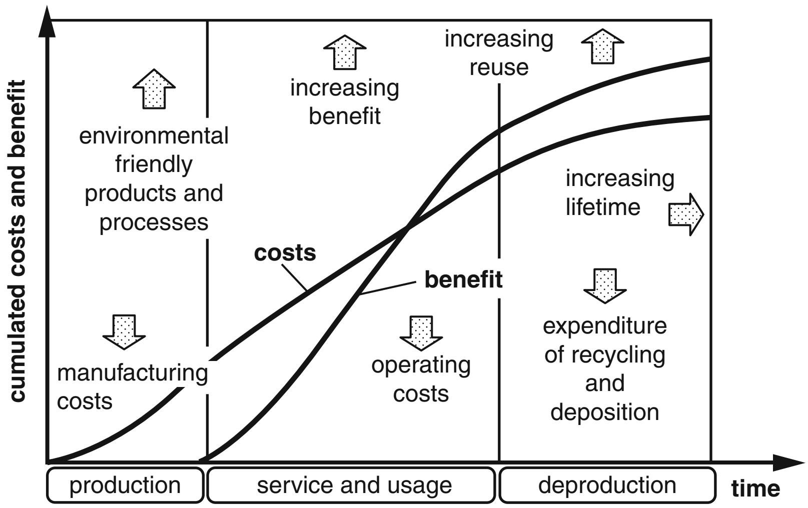
History

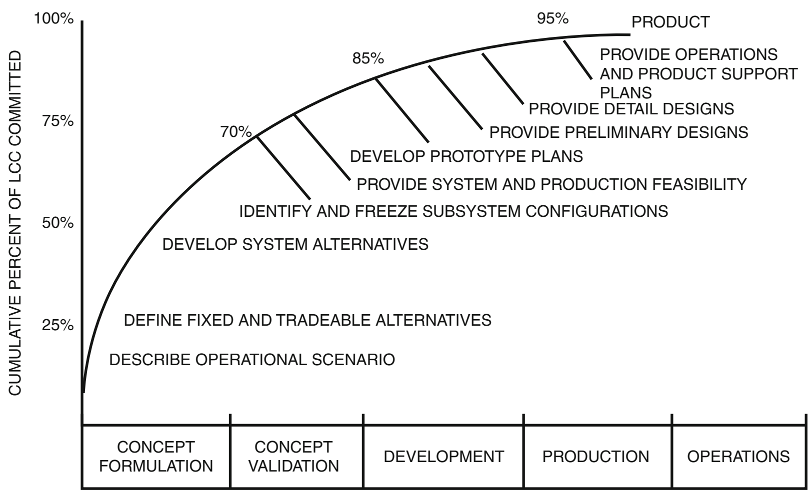
LCC was developed by the US Department of Defense (DOD) during the mid-1960s and has been used ever since as a tool for large infrastructure projects such as military facilities, buildings, and oil refineries. From the 1980s through the early 1990s, different cost models were developed for LCC estimation, 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 as shown in Fig. 2. 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).

Life Cycle Cost, Fig. 2 Cost and benefits during product life cycle (Westkaemper and Osten-Sacken 1998)





Life Cycle Cost, Fig. 3 Cumulative percent of LCC committed (U.S. Department of Energy 1997)

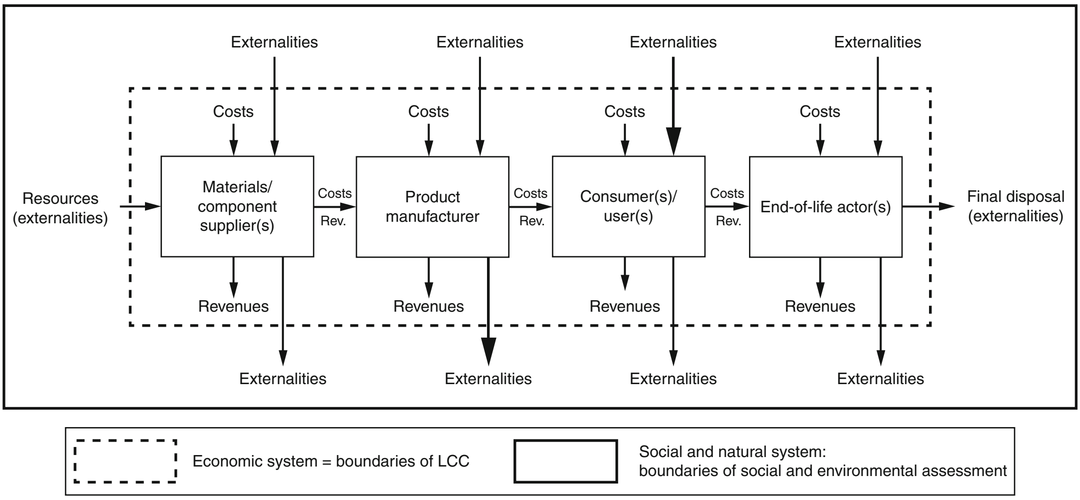
Potential Benefits

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 as depicted in Fig. 2. 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 as shown in Fig. 3.

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,



Life Cycle Cost, Fig. 4 The conceptual framework of LCC (Brown and Straton 2001)

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 as shown in Fig. 4.

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 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.

Discounting: This is defined as a percentage of the value of money that is changed over time between 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

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]

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

Jack Jeswiet
Queens University, Kingston, ON, Canada

Definition

A definition for Life Cycle Engineering (LCE) is "engineering activities which include the application of technological and scientific principles to manufacturing 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

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

(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 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 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 is 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 Management

▶ Product Life Cycle Management

Linkage Model

▶ Mechanism

Locating

▶ Positioning

Logistic Curves

Peter Nyhuis
Institute of Production Systems and Logistics, Leibniz University Hannover, Garbsen, Niedersachsen, Germany

Synonyms

Production operating curves

Definition

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

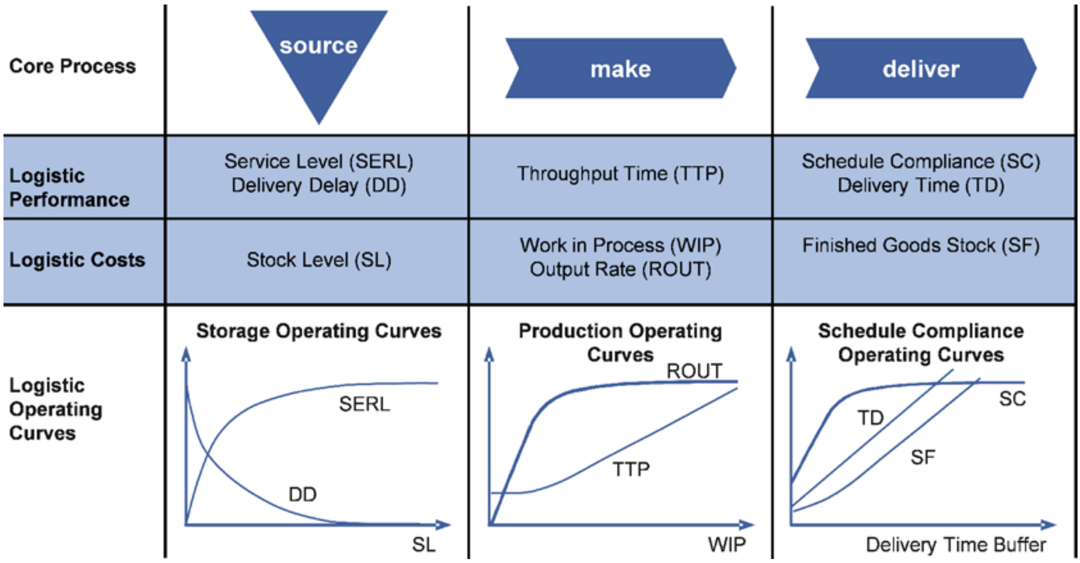
Extended Definition

The company-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 create a field of tension between the logistic performance and logistic costs (Fig. 1, middle). Moreover, the objectives to some extent both contradict and complement one another. Finding an optimum within this field of conflict is impossible for enterprises. Instead, the company has to position themselves 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 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, output 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 regards to procurement, can be applied. In comparison, with a make-to-order production,



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

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, i.e., 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 (Nyhuis and Schmidt 2011).

Theory and Application

The Logistic Operating Curves are impact models derived either from deductive or deductive/experimental modeling. They reproduce 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 regards to quantity and due date). The greater the supplier's due date reliability the steeper, for example, the slope of the Service Level Operating Curve is. This means that in order to ensure a desired service level, a lower stock level is required. A number of parameters, e.g., technical disruptions, load variance, capacity flexibility, or lot sizes, just to name a few 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

Logistic Curves, Fig. 2 Application areas for Logistic Operating Curves

<table>
<tr><th>monitoring and developing process reliability</th><th>monitoring and developing process capability</th></tr>
<tr><td colspan="2">logistic positioning
• settling adequate operating ranges
• verifying consistency of logistic objectives</td></tr>
<tr><td>process monitoring
• evaluating processes
• determining potential for logistic improvement</td><td>selecting planning and control strategies
• lot size determination
• scheduling
• order release</td></tr>
<tr><td>production planning and control
• determining consistent planning parameters (delivery time buffer, safety stock, throughput times etc.)</td><td>designing production processes
• designing production structures
• determination of the customer decoupling point
• planning layout</td></tr>
</table>

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 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

Sotiris Makris, Kosmas Alexopoulos and George Chryssolouris
Laboratory for Manufacturing Systems and Automation (LMS), Department of Mechanical Engineering and Aeronautics, University of Patras, Patras, Greece

Synonyms

Flow of materials; Material transfer; 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 difficult (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).

Methods and Tools

Economic systems are generally modeled mathematically. In this paragraph, some of the basic methods common to such systems will be presented. 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).

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

Minimize or maximize $f(x1, x2, \ldots, xn)$
Subject to the constraints:

$$
\begin{aligned}
&g1(x1, x2, \ldots, xn)\diamondsuit \mathrm{b}1\\
&g2(x1, x2, \ldots, xn)\diamondsuit b2\\
&\ldots\\
&gm(x1, x2, \ldots, xn)\diamondsuit bm
\end{aligned}
$$

where the symbol $\diamondsuit$ 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 $f(x1, x2, \ldots, xn)$ and each constraint function $gi(x1, x2, \ldots, xn)$ are linear in their arguments. If there is an additional constraint that the decision variables $x1, x2, \ldots, xn$ must be integers, then an integer program is a *linear* one.

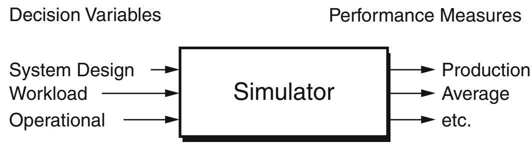
Dynamic programming is a method for solving problems that can be viewed as *multistage decision processes*. A multistage decision process is a process that can be separated into a number of sequential steps, or stages, which may be completed in one or more ways. The options for completing the stages 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 server 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*. On an abstract level, search methods find solutions by exploring paths. What distinguishes one search method from another is that of the heuristics, which decides how the exploring is to be done (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.



Logistics, Fig. 1 Computer simulation

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).

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 (Fig. 1).

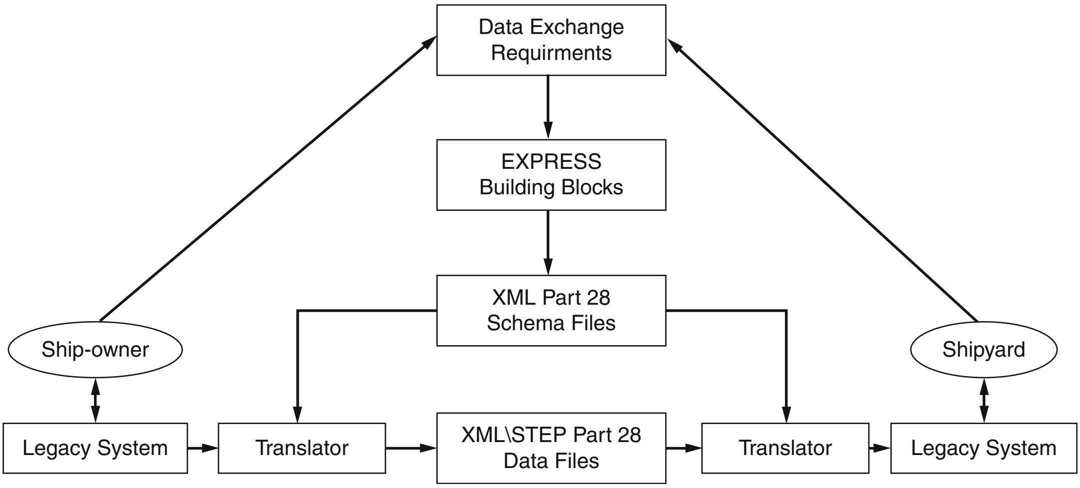
Logistics and Information Technology

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 addition, the production processes taking place at a production facility should be coordinated in such a way that the productivity of the production resources to be maximized parallels the reduction of the delivery time. The requirement for communication among software systems can be addressed by the adoption of neutral data format. 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).

Applications

Ship Repair Industry

The computer-based data exchange throughout the value-added chain needs to be performed in minimum effort and minimum time, allowing the easy and fast flow of information among the partners. This implies faster execution of the business process by optimizing the performance of the supply chain. The requirement for communication among software systems can be addressed by the adoption of a neutral data formats. The business process for the repair of a ship involves a large number of interrelated partners. The main participants are as follows: the shipowner that may be represented by his shipping or managing company, the emergency response company, the salvage or tug company, the shipyard, the classification society, the hull insurer, and the P&I club standing for the protection and indemnity club. The business process is complex for a number of reasons: (a) the ship is in the sea and has to send the repair-related data to a large number of actors in a fast, easy, and reliable way; (b) the repair work is not known from the beginning, and a lot of repair items are identified during inspection at the shipyard; (c) a large number of actors, performing manufacturing activities, are involved in the repair; and (d) the activities performed in the shipyard and by the suppliers are interrelated. Due to the nature of the maritime industry, the partners must communicate in a fast, easy, and reliable way by exchanging information about the ship, the casualties that may have occurred, as well as information for coordinating purposes. In Makris et al. (2008), they discuss how information technology, particularly the ISO 10303 (STEP) and Extensible Markup Language (XML), can be jointly utilized to support the communication and data exchange among partners, within the ship repair industry, worldwide, and using the web as a communication layer. STEP modeling in maritime involves the adoption of the building blocks approach. In Makris et al. (2008), a set of



Logistics, Fig. 2 Exchange mechanism from the shipowner to the shipyard

building blocks has been developed, representing the data exchange between the shipowner and the shipyard for a typical ship repair scenario. These are the *enquiries_data*, describing the customer's enquiry; *tenders_data*, which describe the data for the tender procedure; *contracts_data*, data related to the contract between the shipyard and the shipowner; *invoices_data*, which describe the data in the invoice; and, finally, the *jobs_specifications*, which provide information about the repair and maintenance jobs. Having the model in EXPRESS format, the next step is to transform this model to its XML equivalent. The reason for this conversion is that based on the XML form of the model, a software application can be developed that will be using this XML-formatted model and will be producing XML-formatted documents that will be compliant with this model. The overall procedure for establishing a data exchange mechanism from the shipowner to the shipyard is shown in Fig. 2.

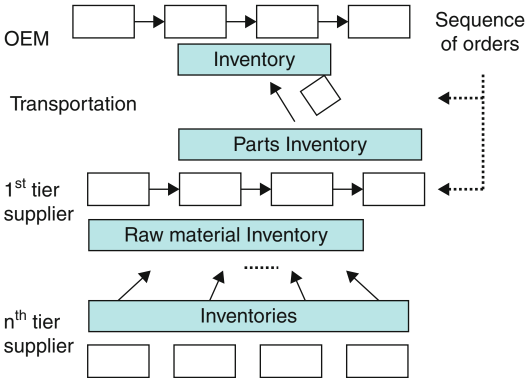
The benefit of modeling data by using the EXPRESS modeling language is that it is based on standard modeling approaches, which are defined by the ISO 10303 specifications, and reuses existing data models that are already standardized by the ISO committees. This way, the new models help to avoid remodeling information that is already specified elsewhere. The conversion of the EXPRESS data models in their XML equivalent offers the advantage that XML files can be read and written based on the XML specifications. The XML-formatted data can then be used, due to the advantages of using XML-formatted information, for data exchange. Open tools can be used to read XML-formatted data since XML is a standard that is well established in current industrial practice.

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. 3 below. 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.

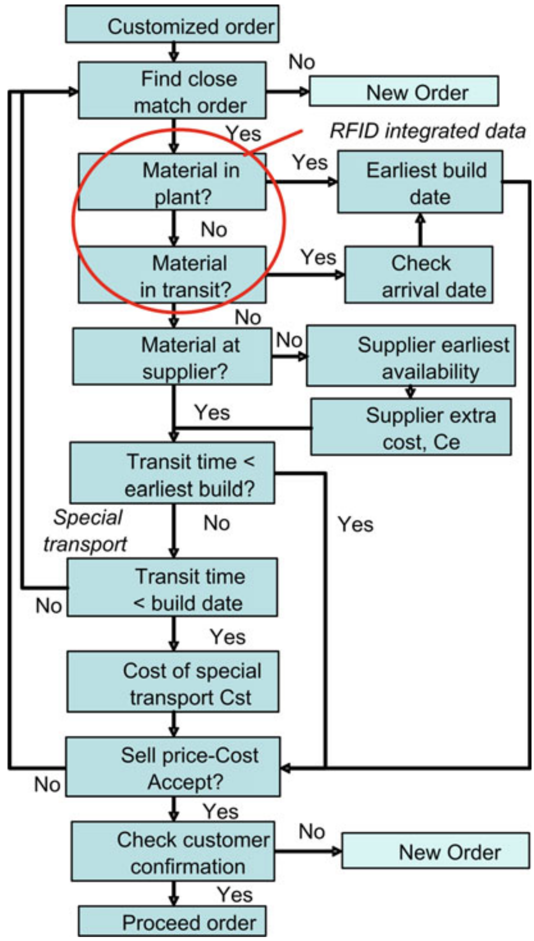
The currently available organizational structure and the information systems, at least in the automotive industry, are not capable of supporting



Logistics, Fig. 3 Structure of a typical supply chain in automotive industry

efficiently the need for building customized products. These systems are implemented based on the mass production concept. The requirement for producing highly customized products imposes the need for reconsidering the organizational structures and supporting them with the advanced information technology. In Makris et al. (2011), they discuss a supply chain control model that allows the querying of supply chain partners regarding the feasibility and cost efficiency of acquiring the necessary parts for the production of a customized product. This model is implemented in the form of a web-based software system. The principles of the supply chain control logic are illustrated in Fig. 4 below.

A customer at dealership customizes a vehicle based on standardized vehicle configurations. The OEM receives the order and is checking for a prescheduled order that could be modified to produce the customized order. The OEM schedules and allocates a slot in the production for the pre-configured vehicles. In case that a vehicle being a close match to the customized order does not exist, then a new order is placed. Otherwise, the customized order is mapped to a production slot for a pre-configured vehicle. The business logic checks the time feasibility for building the product by checking a series of factors, specifically the material's availability in the time frame that the product is scheduled for production and the extra costs that may occur. In terms of checking the material's availability, the control logic queries the supply chain



Logistics, Fig. 4 Automotive supply chain control model

about it in the OEM plant, in transit from the supplier to the OEM, and in the supplier's parts inventory, and in case there is no availability, it queries the supplier as to when the product may be available. Then, depending on the result of the feasibility check, the control logic evaluates the extra cost provided there is such. Particularly, if the part is in the OEM's inventory, then there is no extra cost. If the part is in transit, then again there is no extra cost. However, if the part is in the supplier's inventory and has to be transferred soon enough to fit the production slot which means that it will need special transportation, this cost will certainly be considered for the decision. Special transport includes unplanned requirements for fulfilling it, such as extra space in the truck. The supply control logic is implemented in Business Process Execution Language (BPEL) engine and deployed as a set of web services. The RFID data collection is realized by having RFID readers gathering data from items leaving a supplier's warehouse and items entering an OEM's warehouse. Each reader holds the data in an internal database and exposes a web service interface for retrieving it; the control logic is using this interface for calculating material availability in transit and in the OEM's inventory.

Cross-References

► Material Flow

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Loose Abrasive Machining

► Lapping