FP7 Project

“ENergy Efficient Process pLANing system”

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MANAGMENT BRIEF

The main purpose of this deliverable is to:

- Identify the processes (conventional and non-conventional) and handling equipment that will be studied in ENEPLAN
- Provide the State Of The Art of the above technologies, focusing mainly on their energy efficiency.
- Assessment and classification of them in terms of certain criteria, such as:
  - Eco-friendliness
  - Energy consumption & efficiency
  - Quality assurance
  - Cost
  - Process and line flexibility
  - Time efficiency
- Review and evaluation of the existing simulation models and machine tool behavior models for the selected processes.

Further outlook is provided in the following sections.

CONTENTS

1 INTRODUCTION

European manufacturing plants provide a number of different processing possibilities for manufacturing a specific product. Different advantages and limitations may arise from each one of these processing possibilities that are function of both the geometry, material and the batch size of the part to be manufactured. However, one of the main driving forces in today's production is the environmental friendliness as well as the quick response to market demands through an efficient process planning approach.

The status quo industry today can be summarized into the following:

- Large unnecessary energy use in the industrial sector (20-50%)
- Highly demanding customers need short lifecycle products, increasing the need for flexible manufacturing processes
- Increased needs for fast alternative process plans proposals, for the manufacturing of a specific product

The ENEPLAN vision is the development of a MetaCAM tool that will optimize the process planning in terms of energy efficiency, environmental friendliness, and quick response to market needs, cost and flexibility. The projects key objectives can be summarized into the following:

- Environmental footprint reduction for metal formed components by selecting a more energy efficient combination of process among those available in the already existing supply chain.
- Energy efficiency improvement in working conditions
- Multi-process, multi-company distributed control

Preparation of the business cases

In order to test the developed MetaCAM tool three Industrial pilot cases will be investigated.

Automotive (IAM & CRF)

IAM together with CRF developed the automotive business cases. The processes generally involved in the fabrication of these components are drawing, bending/forming, cutting, piercing and welding. These fabrication processes are characterized by an uncertainty in the production volume. This drives to a multiple choices scenario that fits well within the ENEPLAN mission. Getting a flexible solution means to easily face changing in cycles and within the supply chain and to solve the problem caused by dissaturing an initial investment designed for the maximum capacity.

The potential reduction in energy consumption in these cases is estimated, on lifecycle basis, of at least 40% compared to current situation, taking advantage from the use of new servo drive presses, from energy efficient bending, laser cutting and from optimized planning. One single component of this kind accounts for 10 MJ/lifecycle that means a potential energy reduction of 4 MJ per component, 7.2 GJ per production life (6 years).

The first component which has been selected among those being part of a subsystem of the car body is a structural frame to carry CNG tank on eco-fuel versions of a LCV.

1. **Lattice structure – n. 2 and 3 tanks**

<u>Actual production cycle:</u>

1. Laser cutting
2. Sawing + Bending
3. Projection welding
4. Spot welding
5. CO2 welding

Material used: steel (FeP12)

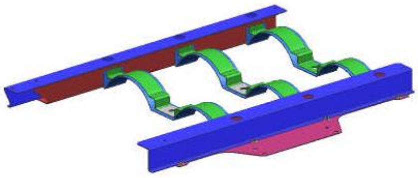


Figure 1: Lattice structure (2 tanks)

2. **Cover – n. 2 and 3 tanks**

Actual production cycle:

1. Sawing & Bending
2. Spot welding

Material used: steel (FeP02)

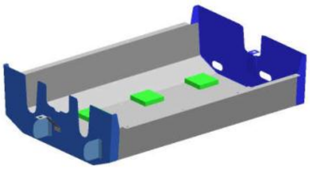


Figure 2: Cover (2 tanks)

Main processes:

- laser cutting
- sawing
- bending
- projection welding
- spot welding
- CO_2 welding.

Handling equipment:

The handling is mostly based on trolleys used to pick up components/sub-assembly from buffers. There are small buffers dedicated to each component or sub-assembly. These materials are then handled by trolleys.

Remarks:

Referring to the IAM context, handling has to be intended also in terms of delivery routes. Servo drive presses concentrate in itself advantages of conventional presses such as flexibility of a hydraulic press thanks to the possibility to control and each working cycle phase and productivity of a mechanical press. The slide profile motion can be controlled accurately, can be divided into phases and can be easily adapted to a new configuration. All these aspects allow achieving higher productivity, higher quality standards and more flexibility. Mechanical presses are good for high volumes of relatively easily formed parts, but they are not well suited to deeper draws or more difficult to form parts. On the other hand, the slow cycle time of a hydraulic press, while a detriment to large volume production, is ideal for these kinds of components. Servo press does not have a single fixed motion curve: unlike a mechanical press which is in continuously cycles up and down at a fixed speed or a hydraulic press whose speed and force are related to the fluid flow, servo press, thanks to the servo motor, are free to operate over a wide range of speeds and pressures. For this reason servo press can reproduce quick hard strokes typical of a mechanical press, or the slow forming cycles of a hydraulic press. Moreover, servo presses, unlike a higher initial cost, present a lower energy consumption and maintenance/operating cost in respect to conventional presses; for these reasons it represents an interesting case of study for the ENEPLAN project.

A servo press which presents these features can be developed within the ENEPLAN project in collaboration with project partners and can be integrated into a real production cycle within IAM Consortium. The automotive business case should focus on the fabrication of a specific component representative of a network that involves both OEM and SMEs. Regarding forming processes, machine fleet available within our Consortium include a wide range of conventional presses such as hydraulic, eccentric and coining presses. Forming by the means of servo drive presses must be assessed within the project as an alternative solution. Interesting technologies for this BC are also laser welding and laser machining (in particular laser cutting). For what concerns punching processes, punching machines with multiple geometry axes are available. They represent a good example of flexibility, but costs and cycle time in this case are not challenging in respect to market needs.

This activity aims at having a complete and detailed database of machine fleets available within the Consortium. These data can concern also energy consumption, capacity and capacity factor and other specific information that can be relevant for the ENEPLAN project.

The **second component** that has been selected is a LCV two seats bench or back of a single seat. This business case aims at comparing the actual process with an alternative one, which entails the design of a new archetype for an automotive seat structure which, leveraging on new materials (i.e. high strength aluminum or high strength steel), will deliver an outstanding ratio performance / weight while maintaining a competitive cost compared to current solutions.

IAM will undertake the data collection about the reference case**.** In particular it will identify the detailed operations sequence with respect to the incoming material, by assessing each process step (energetic consumption, cycle times and operations sequence) to obtain the final assembled product. Then IAM will manage the proposal for the alternative solution (CAD) and realize mold for the case study of new technologies. Finaly, IAM will undertake the fabrication and the assembly of the final demonstrator

Phases 1 and 2 will involve ISRINGHAUSEN. Phases 3 and 4 will involve another company within the IAM Consortium or eventually another project partner. The development of innovative/alternative technologies will be carried out by CRF

Actual production cycle:

1. Manual and MIG welding
2. Bending and flattening
3. Cataphoresis
4. Seats dressing up (stuffing) and covering

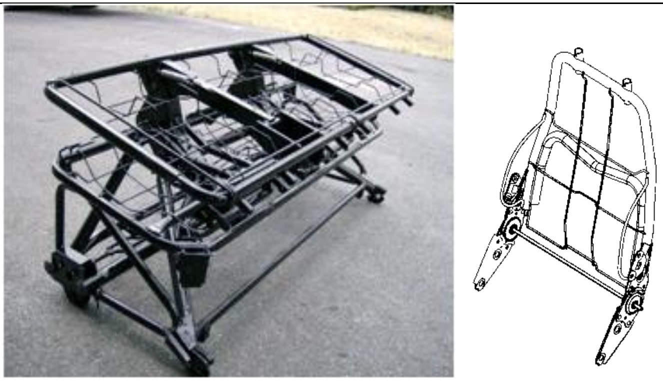


Figure 3: a) LCV two seats bench, b) back of a single seat

Alternate production cycle:

1. Hydroforming
2. Gas forming
3. Laser welding

Material used: Steel

Alternate material used: Aluminium

Handling equipment**:**

1. Truck/trolley
2. Carousel
3. Conveyer

Remarks:

Referring to the IAM context, handling has to be intended also in terms of delivery routes. One limitation could be the strict dimensional tolerances required by the joint This business case aims at comparing the actual process with an alternative one, which entails the design of a new archetype for an automotive seat structure which, leveraging on new materials (i.e. high strength aluminium or high strength steel), will deliver an outstanding ratio performance / weight while maintaining a competitive cost compared to current solutions. The incoming raw material is represented by steel bars and other stamped/bent parts.

Forming technologies such as hydroforming for HSS or gas forming for aluminium alloys, can enable a high degree of function integration, and joining technologies such as laser welding can guarantee an excellent ratio of productivity vs. costs (remote laser welding, low distortion arc welding, and plasma welding/brazing). Furthermore a typical seat structure is made of several components (typically more than 20) since the basic architecture is based on welding simple stamped or bent metal parts. By using alternative innovative forming technologies for tubes (i.e. hydroforming or gas-forming) several functions could be integrated in fewer components with a cost reduction which is expected at least to compensate the higher cost of the new forming technology being used (source Italian national project SAPEM for hydroforming). Moreover Remote Laser Welding can cope with single side access imposed by tubular sections achieving at the same time high quality, very good mechanical behaviour, and high productivity.

The potential weight reduction in this case is more than 10% which means on a C class vehicle a potential reduction of around 8kg. Moving towards aluminium would mean a further weight savings of 20% with a minimum cost increase of 3€ for each kg reduced (source EU project SLC), sustainable for premium vehicles

Aeronautics (NEW, AMRC, TEKS)

The NEW together with AMRC & TEKS developed the aeronautics business cases.

The **first case** is the manufacturing of a Loading Ramp Hinge. The product has been manufactured in house and the customer has decided to outsource the product. NEW will initially re-method the manufacturing process in a similar vain to that followed by the customer. The aim of the project is to significantly reduce both cost and energy involved in the production of the component

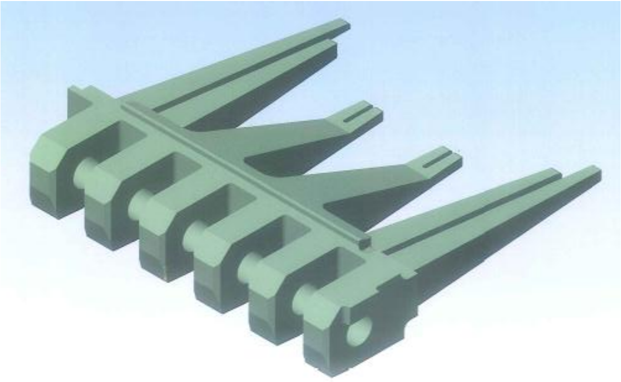


Figure 4: Loading Ramp Hinge of a military aircraft

Main processes:

- Sawing,
- Turning,
- Milling,
- Drilling,
- Boring,
- Heat Treatment,
- Fixtures & Overhead Cranes

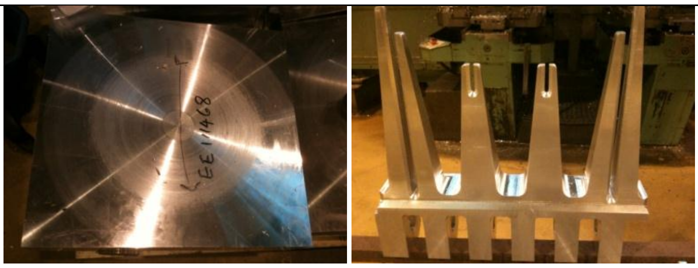


Figure 5: a) Raw material stage 1 b) Finished component

Milling, Drilling & Boring are currently known processes but could be investigated in order to achieve faster production rates. **Water Jet** has restrictions on tolerances, cost & quality from abrasive residue but can be a possible alternative, because of the material savings from proper nesting. **Wire EDM** cost could be offset by stacking. Process tolerance is acceptable but the breakdown rates should be assessed. **Fixturing** and **material handling** should be looked in order to reduce energy, risk and time. Material grain flow direction must be maintained.

The **second case** is the manufacturing of an aluminium support bracket.

This **airframe link** has a production of 1000 annually. Currently is made out of AL6061T6, However, ideally the use of Aluminium Matrix Composites (AMC) should be used in order to achieve weight and strength benefits.

The main goals is to identify the alternative means of manufacture (e.g. 5 axis waterjet machining or 5 axis VMC) versus current 3 axis machining centre or indicate better ways of utilising current capabilities (production planning). The aim would be to identify means to significantly reduce both cost and energy involved in the production of the component.

Main Processes: Milling & drilling on Haas TM1 (3 axis)

Milling (3axis VMC) is energy intensive compared to some alternative processes like laser and AWJM. The low use of coolant will not have much of an impact on environmental footprint because no covers / guards. The **Drilling** (3 axis VMC with no through-coolant) used in this business case, can be improved in terms of process quality and efficiency. **Laser cutting** is an interesting alternative to milling because of efficiency gains and it would be explored for the use of profiling. **WaterJet** can be used to some materials like aluminium, which are difficult to laser. Therefore, precision waterjet could provide a solution (and environmental advantage); however, high consumption of water, cost & abrasive residue needs investigation in order to achieve optimisation

Household (Gorenje)

Gorenje developed the Household business cases. The **first case** is the manufacturing of a sheet metal forming tool. These parts are basics for almost every deep drawing tool. Here are 3 parts, die, blank-holder and punch.

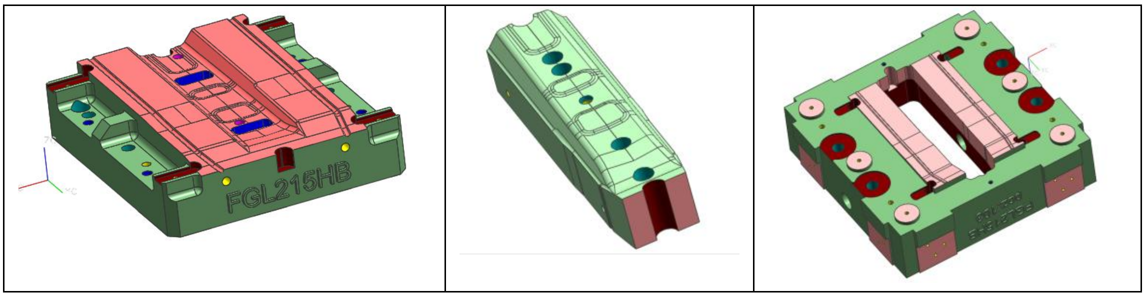


Figure 6: a. Die, b. punch, c. Blank-holder

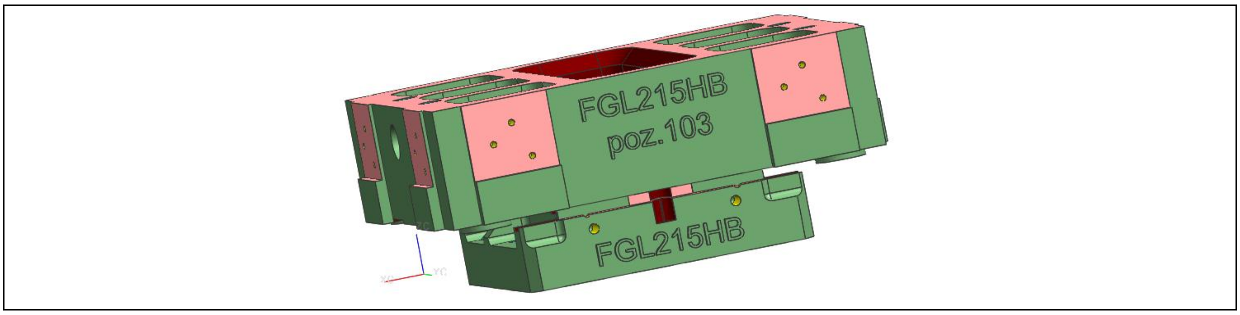


Figure 7: All three parts together

All of them are produced in Gorenje facilities. There are more different ways to get those parts. Two most useful ways are described for **part – punch** (outer dimensions 112 x 445 x 88mm).

Technical aspects

Current process plan:

- Raw material: steel 1.2379 (square block) – Mass = 40 kg

Milling 2D → Drilling → Milling 3D → Hardening → Grinding → Milling 3D

Figure 8: Punch current process plan

Case 1 material:

Raw material: steel 1.2379 (square block) – Mass = 40 kg (120 x 455 x 95mm)

Case 2 material:

Raw material: steel casting (3D shape with addition – approximately 5mm) - Mass = 30 kg (120 x 455 x 95mm)

Main processes for Case 1:

- Milling on the grave dimensions (2D milling machine) – 112,5 x 455,5 x 88,6 mm
- Drilling from both side – For easier transporting
- Milling 3D to the shape with 0,5mm addition (3D milling machine)
- Hardening to 54-56 HRc
- Grinding on the final dimensions: 112,00 x 88,00 mm
- Milling 3D – precise machining (3D milling machine) – Final shape

Main processes for Case 2:

- Grinding on the final dimensions (2D milling machine) – 112,00 x 88,00 mm
- Drilling from both side – For easier transporting
- Milling 3D – precise machining (3D milling machine) – Final shape
- Surface Hardening – with laser

Remarks:

In Case 1 more material & milling is needed, which means that more waste and more energy is used.

In Case 2 more expensive casts but then we have less milling is needed. Instead of hardening of all material only surface hardening with laser takes place which is also more expensive than normal hardening.

This two cases show two ways to get the parts for Gorenje tools. Both ways are used, and for one type of shape it could be clear which scenario to choose but in some cases it is not so clear. Gorenje would like to analyze which scenario is better based on cost, machine availability, and energy consumption and also which scenario is more environmental friendly

The main problem is when milling very hard steel material (up to 65HRc). Reaction forces on the machine are in this case very big therefore the machining has to be slower and the wearing of the tool is higher.

Another problem is consumption of the raw material. The Parts that Gorenje produces are all very different shape and from different material. Therefore the production scenario for making them is also very different. In some cases (depends of shape, material…) saving becomes very difficult and a tool for the final selection of the right production scenario is needed.

Handling:

Manually

The **second case** is the manufacturing of front panels for refrigerator‘s doors 6 different end versions.

Material:

The Initial sheet metal plate: Thickness: 0,7 mm Sheet material: X5 CrNi 1810 VZ039 Dimensions: Coil

High quality demands:

No sharp edges allowed

- Visible surfaces without aesthetics faults (scratches,…)
- All dimensions in tolerances

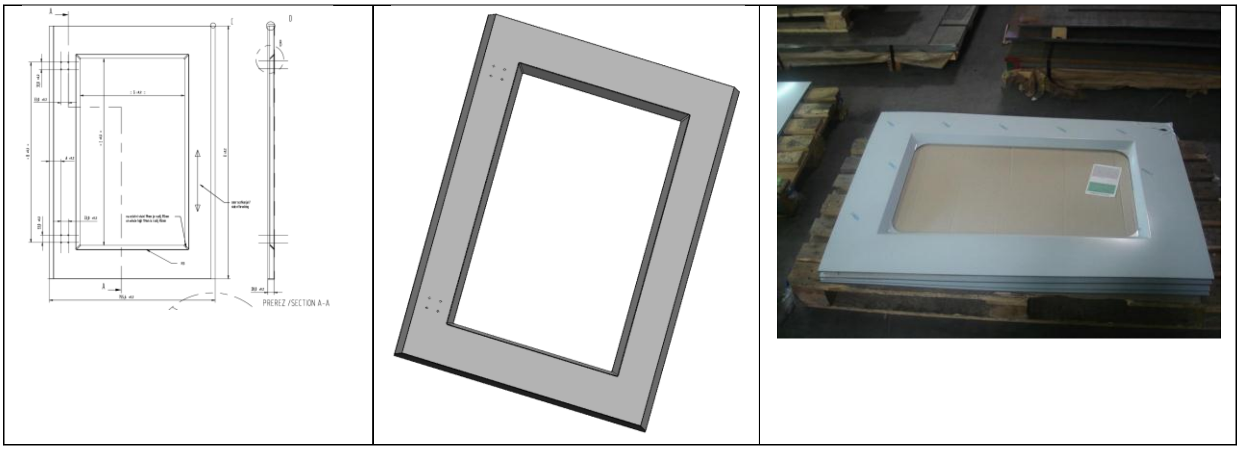


Figure 9: a. Dimensions & tolerances b. CAD model of Front panel c. Uncutted panel,

Actual production cycle:

1. Blank cutting – 2D laser
2. forming (drawing)
3. 5 axis laser cutting
4. Bending
5. Welding & grinding

Alternate production cycle::

- Punching
- Incremental sheet metal forming
- Bending with tool and press

Processes & Handling equipment		AUTOMOTIVE (CRF, IAM)		AERONAUTIC (NEW, AMRC, TEKS)		HOUSEHOLD (GORENJE)	
		CNG tank	2 Seat beanch or back of single seat	Loading Ramp Hinge of a military aircraft	airframe link	sheet metal forming tool	front panels for refrigerator's doors
Conventional	**Arc- welding (MIG)**	7	7		3		
	Turning			1	5		
	Drilling			3	8	4	
	Milling			10	10	10	
	Sawing	7		1	4	3	
	Grinding				4	6	
	Punching	7			2		9
	Forming (including servo-drive presses)	10			2		7
	Bending	7	7				8
	Heat Treatment			3			
Non-conventional	**Laser Machining (cutting, drilling…)**	9		4	2	9	10
	Laser Welding	7	10				
	Electrical Discharge Machining (EDM)			6 (wire)	3		
	Water jet			6	4		
	Thnixoforming			2			
	Hydroforming		10				
	Gas forming		10				
	MIM			1			
	Friction welded assembly			2			

Table 1: Ranking from 1 to 10, based on current the interest to these technologies.

2 ACADEMIC STATE OF THE ART

2.1 INTRODUCTION

Manufacturing processes include a wide variety of operations. All of these processes take material inputs, including working materials and auxiliary materials, and transform them into products and wastes. Similarly, the energy inputs into these processes are transformed into useful work, some of which is embodied into the form and composition of the products and wastes, and waste heat. In today's machining, only a minor part of the consumed energy is used for the actual value-adding process, the majority of the energy is used to guarantee stable process boundary conditions (e.g. cooling).

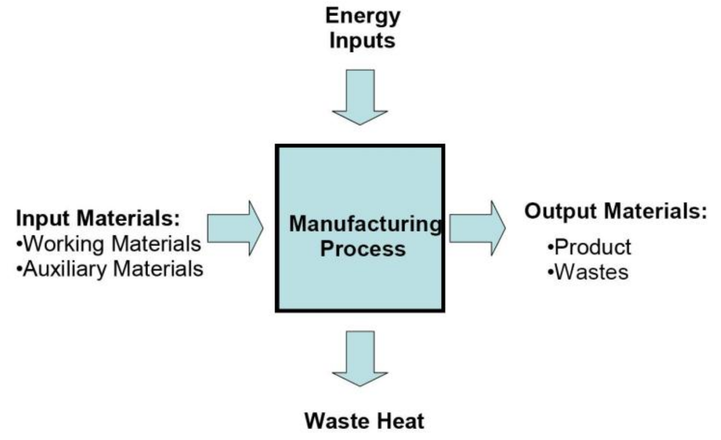


Figure 10: Energy & material inputs &outputs for manufacturing processes [1]

Machine tools sector is one of the most relevant in Europe in terms of GDP (180 billion € of new orders before the crisis, 74 billion €/y in Q2 2010) [2], the sector is composed mainly by SMEs (among machine users: 99.7% by number, 78.2% by GDP, 82.8 by persons employed; among machine manufacturers: 98.7% by number, 49.7 by GDP, 56.5 by persons employed) [3]. In the same way the relevance of the sector in terms of energy consumption is high (>10,000 PJ/y) [4] and consequently high is the financial pressure due to unbalanced demand/offer of energy resulting in energy price increase (as in 2007-2008). Additionally, the recent developments in manufacturing production technologies brought machines and processes of higher performance and higher energy utilization, in order to increase productivity and reliability of the process.

Taking into consideration all the above, the requirement for increased productivity with reduced production cost is crucial. Besides, the growing environmental consciousness of people worldwide has led to legislative pressure (EuP Directive) [5] and it is highly probable that tool machines will be subjected to energy efficiency regulation and classification in the years to come [6].

A universal method of capturing and interpreting the resource and energy consumption is not yet available. The diversity and complexity of machine tools make it difficult to propose a reasonable method. Comparability of the energy consumption and energy efficiency of different process technologies or machine tool configurations can hardly be identified by applying a single component evaluation. Machine internal energy and machine external peripherals are important energy consumers and there are many studies that show that the major share of a machine tool's energy consumption is load-independent and used by peripheral equipment.

2.1.1 Machine tools functions & energy efficiency

Relevant direct value adding functions of the machine tool must be identified for all embracing energetic optimization, thus defining the favoured goal functionality. Auxiliary components, often with a constant load and power consumption, fulfil essential functionality but without proportionality to added value. The goal is to define their share and amount in order to minimize the power consumption to the essential physical minimum. Furthermore, their functionality might be substituted by corresponding technologies or proper dimensions in order to increase energy efficiency. In this sense, the functional modules reflect also the improvement potentials which lead to improvement of the energy efficiency of the entire product. According to document No28a of the ISO TC 39 WG 12, the functional modules which are divided in some main groups, can be further subdivided into sub functions.

A function is defined as the outcome, task, action, or attribute of an object or component. The functional description is general and independent of the system design. Corresponding components can be mapped to one of five main machine functions, as illustrated below (Figure 11) for a generic sample machine tool. The assignment or mapping of mechanical/electrical machine components to the functions is specific for each case.

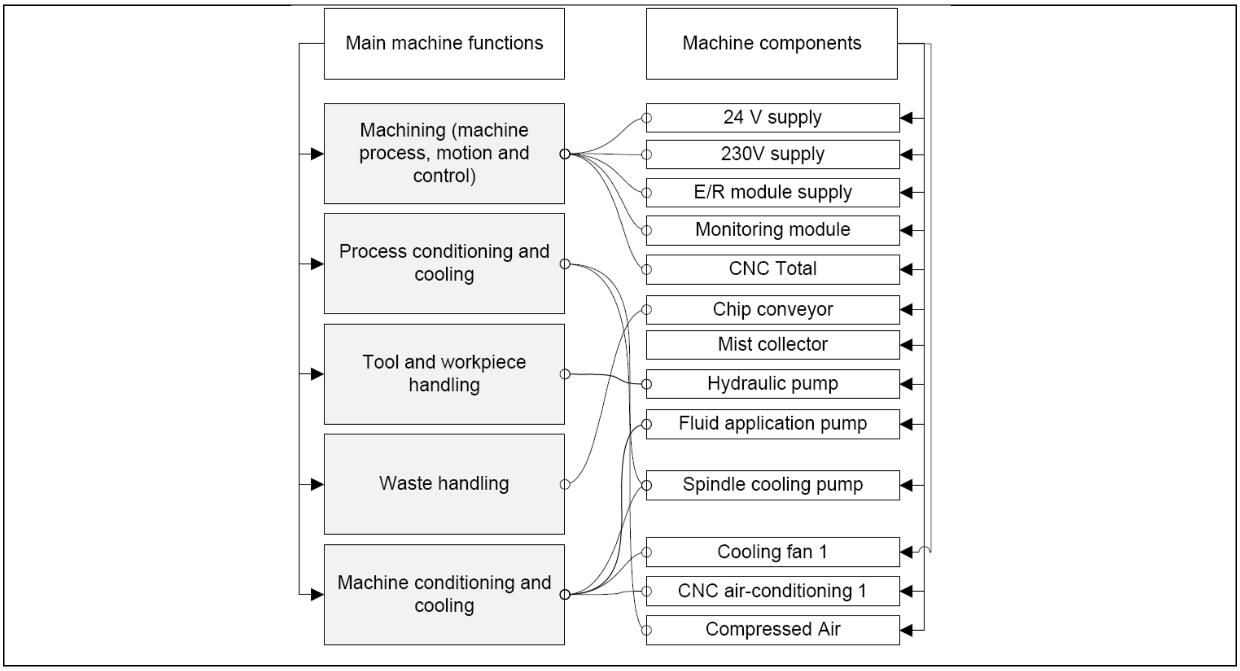


Figure 11: Main machine functions & components

Most components are directly related to one function; for instance, a machining spindle is part of machine motion. In the case of the spindle cooling pump, it contributes not only to process cooling but to machine cooling and also to waste handling by washing away the chips as well. Consequently, the energy consumption of the coolant pump must be split into these three functions, based on measurement or – more frequently – on estimation. A machine tool energy audit is a good way to estimate these shares. The assigned share of the components defines the ensuing evaluation and optimization. Summing up, the functional energy evaluation can be structured into a general part, which is valid for all machine tools, and a specific part, which represents the individual machine tool configuration. The functional oriented energy evaluation represents an approach of a conceptual review of machine tools. It helps to understand the energetic behaviour of a machine tool and establishes a common basis for comparison, energetic evaluations, and further optimizations. The assessment is made based on total energy consumption and data acquisition, which is attributed to defined machine functions. Therefore, the functional view can be seen as a tool, helping to provide a clear depiction of value adding functions. The advantage is to get a simple, easy to understand picture of the energy consumption.

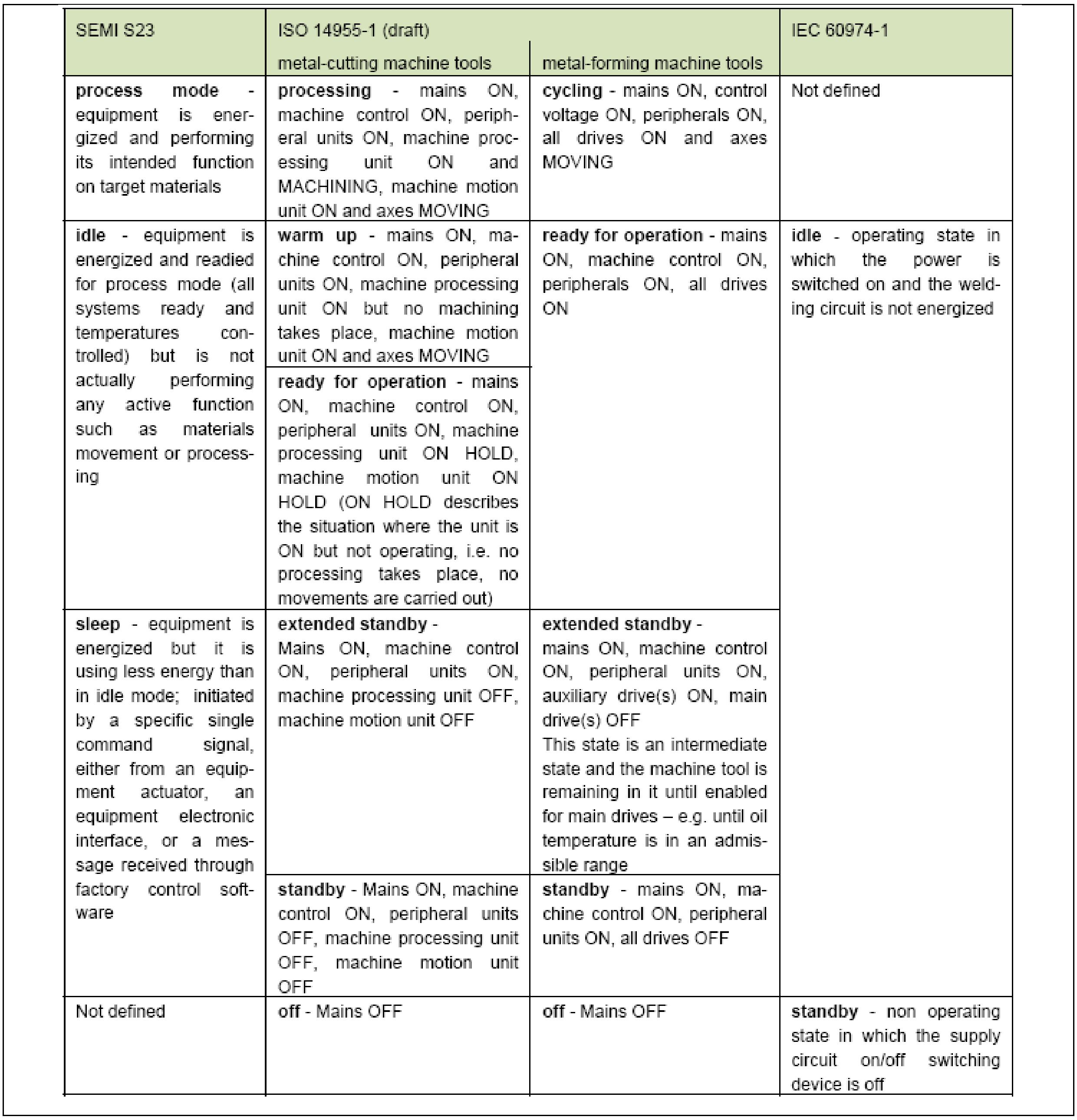
A second point is the obviousness of proportions, leading to the potential field for optimization. Another advantage is the possibility to compare different assemblies of components, either for one machine tool or the comparison of various machine tools, e.g., in decision-making for manufacturing. As it is related to known function-oriented methods in value analysis, target costing, or product development and testing, the concept is easy to adapt and can be implemented in an industrial R&D environment as a complementary tool for energy assessments.

2.1.2 Operating states

Electricity consumption requirements need to be defined on a thorough modes definition. ISO 14955-1 (Draft) defines the operating states for metal working machine tools and Figure 12 provides an abridged version of these in comparison with the modes defined for arc welding equipment in IEC 60974-1 (Draft), and SEMI S23 for semiconductor equipment.

The provision of an interface to an external or internal energy monitoring and control system could be a mandatory requirement for CNC machine tools. Such an interface optionally should enable any of the following:

- Stand-alone solutions are designed in such a way that they can be applied for a broad variety of machines, hence that there is a very low need of specialized machine interfaces.
- Module-based systems are functions usually integrated into the CNC-control software by the control unit manufacturer, in which energy consumption related PLC-commands are addressed.
- As far as external and factory integrated systems are concerned, PROFIenergy is a broadly used protocol in the mechanical engineering industry. The implementation, however, requires the existence of a communication infrastructure based on the open industrial Ethernet standard PROFINET.



SEMI S23	ISO 14955-1 (draft)		IEC 60974-1
	metal-cutting machine tools	metal-forming machine tools	
process mode - equipment is energized and performing its intended function on target materials	**processing** - mains ON, machine control ON, peripheral units ON, machine processing unit ON and MACHINING, machine motion unit ON and axes MOVING	**cycling** - mains ON, control voltage ON, peripherals ON, all drives ON and axes MOVING	Not defined
idle - equipment is energized and readied for process mode (all systems ready and temperatures controlled) but is not actually performing any active function such as materials movement or processing	**warm up** - mains ON, machine control ON, peripheral units ON, machine processing unit ON but no machining takes place, machine motion unit ON and axes MOVING	**ready for operation** - mains ON, machine control ON, peripherals ON, all drives ON	**idle** - operating state in which the power is switched on and the welding circuit is not energized
	ready for operation - mains ON, machine control ON, peripheral units ON, machine processing unit ON HOLD, machine motion unit ON HOLD (ON HOLD describes the situation where the unit is ON but not operating, i.e. no processing takes place, no movements are carried out)		
sleep - equipment is energized but it is using less energy than in idle mode; initiated by a specific single command signal, either from an equipment actuator, an equipment electronic interface, or a message received through factory control software	**extended standby** - Mains ON, machine control ON, peripheral units ON, machine processing unit OFF, machine motion unit OFF	**extended standby** - mains ON, machine control ON, peripheral units ON, auxiliary drive(s) ON, main drive(s) OFF This state is an intermediate state and the machine tool is remaining in it until enabled for main drives – e.g. until oil temperature is in an admissible range	
	standby - Mains ON, machine control ON, peripheral units OFF, machine processing unit OFF, machine motion unit OFF	**standby** - mains ON, machine control ON, peripheral units ON, all drives OFF	
Not defined	**off** - Mains OFF	**off** - Mains OFF	**standby** - non operating state in which the supply circuit on/off switching device is off

Figure 12: Comparison between different operating states defined by different regulations.

Power management requirements have a high potential for improvement, but quantitative requirements (transition times from one mode to another, or even power consumption thresholds in distinct modes) are hardly quantifiable across technologies: Productivity is severely hampered, if too short transition periods from any processing mode to a sleep / standby mode of the machine tool or parts thereof are made obligatory: Warm-up and bringing back the machine to full operating state delays the processing. However, for a given application scenario (job sequence) it is possible to identify a transition time to low-power modes which does not interfere with the majority of the jobs, but still allows for significant power savings (Figure 13).

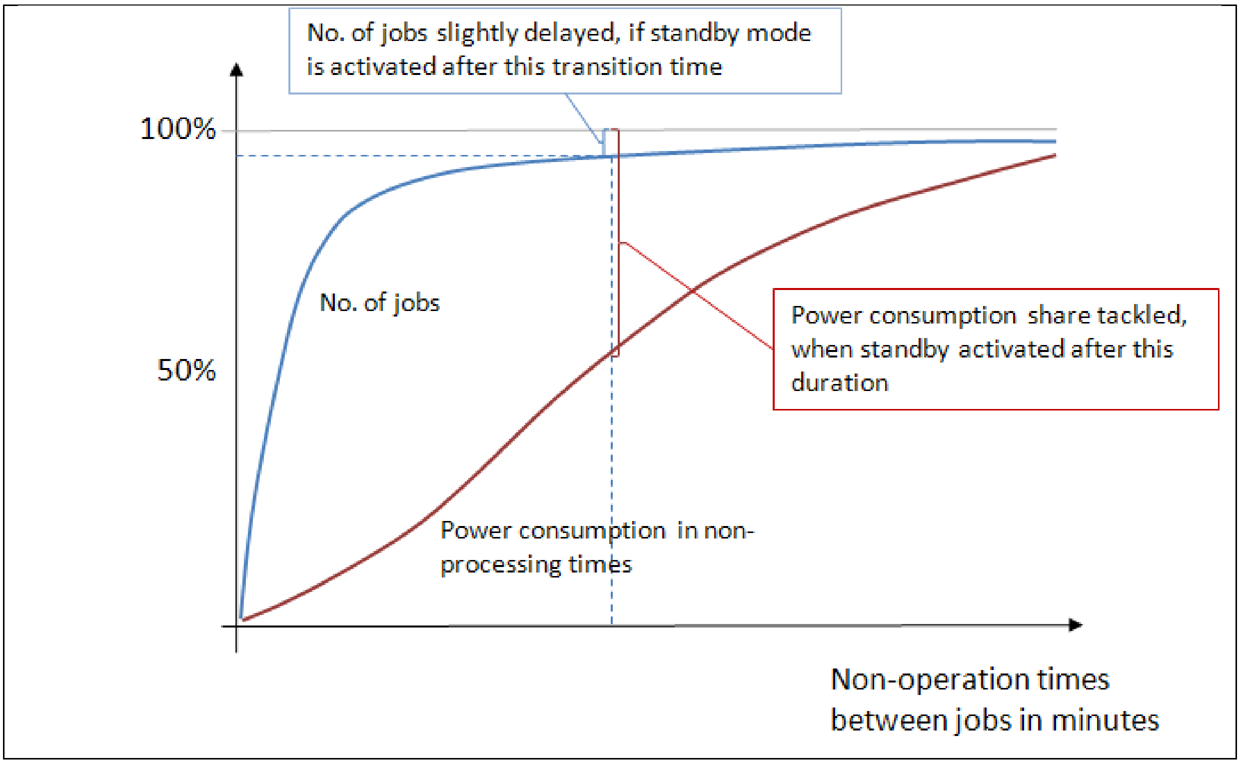


Figure 13: Power saving options between different scenarios

Typically for a given application a correlation can be established between the time span between individual processing jobs and the number of jobs, which are initiated after the respective time span. Such a correlation allows identifying a suitable transition time, but requires essentially an analysis of the individual use case.

2.1.3 Eco-efficient machine tools & European initiatives

Machine tool & related machinery

As a result from an EC Product Group Study related to the Ecodesign of Energy-related Products (ErP) Directive 2009/125/EC [7]. A machine tool is defined as a stationary or transportable, but not portable by hand or mobile assembly, dependent on energy input (such as electricity from the grid or stand-alone / back-up power sources, hydraulic or pneumatic power supply, but not solely manually operated) when in operation, consisting of linked parts or components, at least one of which moves, and which are joined together for a specific application, which is the geometric shaping of workpieces made of arbitrary materials using appropriate tools and forming, cutting, physico-chemical processing or joining technologies, resulting in a product of defined reproducible geometry, and intended for professional use.

The scope of this study [7] covers also “related machinery” which is machinery for professional use that contains components and modules of other machinery, which are similar to those used in machine tools. For clarification: these components and modules might be used in machines, which do not fall under the definition of machine tools as provided above. This broader scope is meant to identify potentially a broader environmental improvement potential in industrial production than only with a focus on machine tools as such. It is intended to follow a modular approach (i.e. machine modules) in the following environmental analysis, taking the machine tools as the starting point, but covering through this modular approach also other (“related”) machinery.

European Union goal

Reducing energy consumption and eliminating energy wastage are among the main goals of the European Union (EU). EU support for improving energy efficiency will prove decisive for competitiveness, security of supply and for meeting the commitments on climate change made under the Kyoto Protocol. There is significant potential for reducing consumption, especially in energy-intensive sectors such as construction, manufacturing, energy conversion and transport. At the end of 2006, the EU pledged to cut its annual consumption of primary energy by 20% by 2020. To achieve this goal, it is working to mobilise public opinion, decision-makers and market operators and to set minimum energy efficiency standards and rules on labelling for products, services and infrastructure.

The expected savings achieved by the implementation of the Ecodesign Directive and its implementing measures in 2010 are negligible. This is due to the fact that the Ecodesign measures are largely starting to enter into effect from 2010 onwards and will then take some years for their effect to be felt fully (as existing products are replaced during their normal life-cycles). Nonetheless, some products meeting Ecodesign requirements will already be on the market in advance of mandatory implementation dates, delivering environmental benefits. It should be noted that energy saving gains from the purchasing of energy-efficient appliances will have a cumulative effect and are not simply 'one-off' savings – thus, earlier implementation of standards by industry is of added value. Certain measures such as requirements for the standby consumption of electric appliances will also have an effect beyond the EU as manufacturers of goods traded worldwide will implement the same technology on all their models irrespective where they will be shipped.

Regulations

After passing the energy efficiency strategy of the European Union in 2006/07 through the Action Plan on Energy Efficiency and the March 2007 Council conclusions, several EU Directives have been ratified to provide an appropriate policy framework for Member States energy efficiency policy. However, the intense debate about the implementation of the Directive on energy end-use efficiency and energy services (ESD) (EC 2006a) has revealed significant differences between ambitious energy efficiency policy targets pursued by the European Commission and the European Parliament, and some Member States being very reserved against a further ‘top-down regulation’. With the new Energy Efficiency Action Plan (EC 2011a) and the “Roadmap for moving to a low-carbon economy in 2050” (EC 2011b) the Commission aims at pushing the debate towards a further harmonisation of ambitions and timetables as well as a further integration of policies and measures at European, Member State and regional level. Through this plan e.g. White Certificates Schemes and energy efficiency funds will most likely be set on the European agenda. Since the publication of the first NEEAP's (National Energy Efficiency Action Plan) in 2007/08, there have been several activities at EU-level either to recast existing Directives or to implement new framework regulations.

What’s the ErP directive

Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009, It is a directive establishing a framework for the setting of ecodesign requirements for energy-related products. The 2009/125/EC Directive of the European Parliament and Council of 2009 defines ecodesign as “the integration of environmental aspects into product design with the aim of improving the environmental performance of products throughout their whole life-cycle”. The Directive sets the framework for adopting EU-wide measures to improve the design of energy using products. The European Commission will adopt specific and tailored ecodesign measures (mandatory requirements) for machine tools. These measures are defined on the basis of an individual evaluation study (preparatory study). While designing their products, manufacturers will have to respect predefined measures, which aim to reduce the environmental impact of products throughout the whole product lifecycle (such as production, use and disposal). The ErP Directive (2009/125/EC) provides the framework for setting minimum performance requirements for environmental aspects of energy-using and energy-related products that are placed onto the market. Although products are assessed with a lifecycle perspective, energy consumption during use is generally the main environmental impact of the product. The implementing measures seek to target both manufacturers and consumers, by promoting better product design that will result in improved environmental performance, lower energy consumption, and ultimately lower costs. Thus, the individual measures either directly or indirectly affect all EU citizens as well as virtually all EU industry or retail sectors through the design, manufacture, sale and use of products covered by the requirements.

2.2 CONVENTIONAL MACHINING PROCESSES

2.2.1 Milling

Current status

Milling is a process of cutting away material by feeding a workpiece past a rotating multiple tooth cutter, being the cutting action, a fast method of machining thanks to many teeth around the milling cutter. The machined surface may be flat, angular, or curved and may also be milled to any combination of shapes. This process has very low set-up cost compared to forming, moulding, and casting processes. However, machining is much more expensive for high volumes; it is necessary where tight tolerances on dimensions and finishes are required. In the past, milling was very important manufacturing process but in last couple of decades milling become even more important because of the advances in machine tool, CNC, CAD/CAM, cutting tool and new technologies. The volume and importance of milling have increased especially in key industries such as aerospace, die and mold, automotive and component manufacturing. Nowadays, the industry have to face with greater and greater requirements of dimensional precision and surface roughness as well as a decrease in costs and manufacturing times which cause a lot of troubles to the manufacturers. But even despite these developments, the process performance is still limited, and the full capability of the available hardware and software cannot be realized due to the limitations set by the process.

In the industry nowadays are in use a lot of different kinds of milling machines. Basically we can divide milling machines into two-axes, three-axes, four-axes and five-axes milling machines and also more complex milling processes such as ball end milling. The choice of which process to choose mostly lays in operators decision which based on material, shape and customers' demands.

Metal machining processes are and will remain the most widespread types of processes in part machining, despite the development of other technologies like die cast or Electro Discharge Machining, milling process can achieve:

- High accuracy.
- Good surface quality.
- Wide variety of forms and dimensions.
- Low costs and high removal rates.

Main problems

The main problems in the milling machining process occur because of high cutting forces and stability of the process. Cutting forces differs from case to case and many things influence on the cutting forces. Cutting forces are different when using different milling machines, different type and different length and diameter of the cutting tool, different material and hardness of the material, different shape, different process parameters… The problems due high cutting forces occur mainly because of the vibration. Vibration has effect on the machine, cutting tool and on the work-piece. Because of vibration it is possible that the machine guidance's can damage or the cutting tool can break and the quality of the work-piece surface can decrease.

Process parameters

If milling conditions are not selected properly, the process may result in violations of machine limitations and part quality, or reduced productivity. The usual practice in machining operations is to use experience-based selection of cutting parameters which may not yield optimum conditions. The process parameters are different basically for every manufacturing part especially in die and mold industry where the products are unique. But in the serial production it is possible to find also some off-line simulation tools for predicting the machining conditions but these systems are rare and also very unreliable.

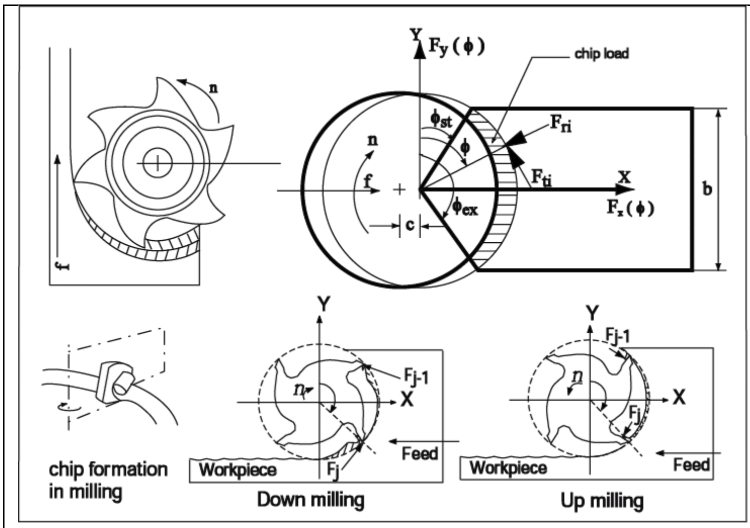
Milling Process Mechanics

Milling is the process of machining flat, curved, or irregular surfaces by feeding the workpiece against a rotating cutter containing a number of cutting edges. Milling process modelling and analysis has been a subject for many studies some of which are comprehensively summarized by Tlusty in [8].

Milling force can be computed associating a cutting force to each mill cutter engaged into the material and performing a vector summation. The force exerted by each cutter depends on chip section, tool geometry and cutting parameters. Chip section is identified by the so-called kinematic analysis of the process: in the simple cases, for a linear tool path and low feedrates, chip section can be parameterized by the depth of cut and the instantaneous chip thickness, which can be modelled by the following expression (by Martellotti):

$$h = csin\varphi \qquad (1)$$

(see figure 14 for symbol definition)



ϕ: *instantaneous angle of immersion*

ϕst, ϕex*: cutter entry and exit angles*

a: *edge contact length*

c: *feed rate*

Figure 14: Milling kinematics

Unfortunately, a great variety of end mill geometry is used in industry [9]. Inserted, helical cylindrical, helical ball, taper helical ball, bull nosed and special purpose end mills are widely used in aerospace, automotive and die machining industry. While the geometry of each cutter may be different, the mechanics and dynamics of the milling process at each cutting edge point are common. A generalized mathematical model of most end mills used in industry can be extracted (see [9]). The end mill geometry is modelled by helical flutes wrapped around a parametric envelope. The coordinates of a cutting edge point along the parametric helical flute are mathematically expressed. By integrating the process along each cutting edge, which is in contact with the workpiece, the cutting forces for an arbitrary end mill can be predicted.

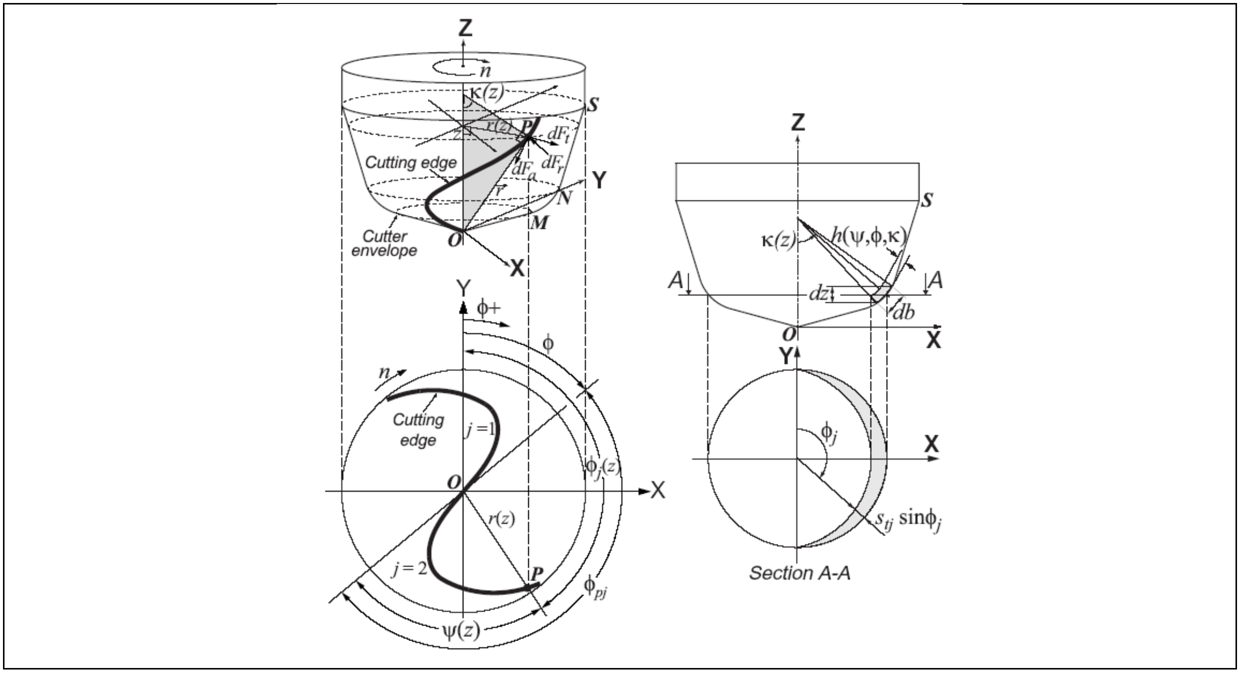


Figure 15: Force differentiation along the flute

These approaches implies the computation of the cutting coefficients that relates the chip section to tangential, thrust and axial force:

$$dF_t = K_{tc} \cdot h(\phi,z)db + K_{te}dS \ ; \ dF_r = K_{rc} \cdot h(\phi,z)db + K_{re}dS \ ; \ dF_a = K_{ac} \cdot h(\phi,z)db + K_{ae}dS \qquad (2)$$

For this reason, mechanics of milling is exploited to reduce the number of tests necessary to compute such coefficients. The basic idea in this approach is to use analytical cutting models relating the chip area to the cutting forces, and to determine the parameters required in the model experimentally when necessary. In case of milling an oblique cutting model has to be employed due to very common helical milling tools. In oblique cutting models, there are several important planes which are used to measure tool angles and write down velocity and force equilibrium relations. The normal plane, which is perpendicular to the cutting edge, is commonly used in the analysis.

After several assumptions, velocity and the force equilibrium equations the following expressions are obtained for the cutting force coefficients in an oblique cutting process:

$$K_{tc} = \frac{\tau}{\sin\phi_n} \frac{\cos(\gamma_n - \alpha_n) + \tan\eta_c \sin\gamma_n \tan\beta}{c} \qquad (3)$$

$$K_{rc} = \frac{\tau}{\sin\phi_n \cos\beta} \frac{\sin(\gamma_n - \alpha_n)}{c} \qquad (4)$$

$$K_{ac} = \frac{\tau}{\sin\phi_n \cos\beta} \frac{\cos(\gamma_n - \alpha_n)\tan\beta - \tan\eta_c \sin\gamma_n}{c} \qquad (5)$$

where

$$c = \sqrt{\cos^2(\phi_n + \gamma_n - \alpha_n) + \tan^2\eta_c \sin^2\gamma} \qquad (6)$$

- τ is the shear stress in the shear plane
- φ_n is the shear angle in the normal plane
- β is the angle of obliquity or helix angle
- η_c is the chip flow angle measured on the rake face.

Also Kronenberg force model is widespread to predict milling forces given the chip geometry: it exploits an exponential relationship between cutting force and chip thickness. Basically, the aforementioned cutting coefficients are modified as it follows:

$$K_{te} = K_{re} = K_{ae} = 0.0$$
$$K_{tc} = KT \cdot h^{-p}$$
$$K_{rc} = KR \cdot h^{-q}$$
$$K_{ac} = KA \cdot h^{-r}$$

Energy consumption in milling process

The most of the energy consumed in the milling process is provided by the spindle unit and, obviously, it increases as long as material is removed from the workpiece. Then, a basic criterion to evaluate the energy consumption consists in associating the necessary spindle power to a given machining operation and integrate it over time.

More relevant than the sole spindle power is the specific spindle power consumption e_s, which is referred to the material removal rate Q_w. The specific spindle power consumption e_s can be calculated by the following equation:

$$e_s = \frac{P_s}{\dot{Q}_w} \qquad (7)$$

with

$$\dot{Q}_w = a_p \cdot a_e \cdot v_f \qquad (8)$$

where

- P_s is the electrical spindle power consumed during the process
- a_p is the depth of cut
- v_f the feed velocity

The specific spindle power consumption describes the efficiency of a cutting process. Thereby a lower e_s means a higher efficiency of the process. Experimental campaign conducted in the framework of the European project NEXT , pointed out that the specific spindle power consumption e_s is significantly influenced by:

- cutting speed (V_c)
- feed per tooth (f_z)
- depth of cut (a_p)
- width of cut (a_e)

The specific spindle power consumption usually declines with increasing these parameters. In the most of cases, the decrease of the specific spindle power consumption e_s with an increasing V_c is caused by a reduction of machining forces at a constant cross section of undeformed chip. A gain of the cross section of undeformed chip by an increase of f_z, a_p or a_e results in a lower ratio of friction energy in relation to the cutting energy. Hence, the specific spindle power consumption e_s decreases with f_z, a_p and a_e. This fact, for example, explains why high-feed end mills seem to exhibit a better performance in terms of energy consumption, since they produce a chip section that approaches the optimal square shape.

On the other side, the situation can be different if the process becomes unstable (chatter occurrence): as the spindle copper losses are proportional to the root mean squared value (RMS) of the torque, the presence of a dynamic component in cutting force may cause an increase of e_s. Therefore, a_p and a_e over certain levels could be disruptive from the efficiency point of view.

Furthermore, the same study states that the cooling strategy does not affect the specific spindle power consumption considerably. Thus, taking into account that the different cooling strategies may imply different levels of power consumption in some accessories (e.g. fluid pump), also this aspect is a potential leverage for an increase of the overall energy efficiency.

The milling machine is a staple of the engineering industry. Frequently used and applicable to so many different machining processes, it is difficult to imagine the world of engineering without them. Evolving from the process of rotary filing in the early 1800s, Eli Whitney is heavily credited with the invention of the first machine. Being one of the oldest machines available, its capabilities have been expanded over the years, and it is widely used across manufacturing industry. Originally developed as manually operated (and some of these still exist) machines, they have evolved over the years to become more efficient through the automation the use of CNC (Computer Numerical Control) programmed by CAD and CAM software. The milling machine follows a similar process to a drilling press, where a drill approaches a part from an axis point (usually horizontal or vertical), but differs in that the work-piece is moved radially against the rotating cutter, and the drills tools cut on their sides as well as their tips.

The past years' development is due to the competition in order to obtain low production costs. In the 70's the introduction of Computed Numerical Control on milling machines, enlarged the possibilities to manufacture more complex parts faster and cheaper.

The cutting tools maintained the competition to build more accurate, much faster and more stable, by developing better materials for the cutting tools, improving the tools geometry and developing new protective layers for the cutting edges, forcing the machine tools designers to achieve higher feed rates and spindle speeds. Also the CAM software development improved the process management by using optimum milling strategies and cutting times of designing the tool path.

Figure 16: Face milling operation

There are many different types of milling machine, some are as follows:

- *Vertical Mill:* A milling machine where the spindle axis is vertically oriented, and the spindle either extends or the table can be raised and lowered. This type of mill includes the "knee-type" or "turret" mills, and the "bed" mill. The knee is a large casting that rides vertically on the column of the machine. The turret has a stationary spindle, and the table is moved both perpendicular and parallel to the spindle axis to achieve cutting. In a “bed” mill, the spindle moves parallel to its own axis, while the table moves perpendicular.

- *Horizontal Mill:* Although very similar to the vertical mill, the horizontal mill tends to include a rotary table, where the part can be rotated to up to 45°. These also include arbor mounted cutters, known as side and face mills, which are used to mill grooves and slots.
- *Ram Mill:* The ram-type milling machine is characterized by a spindle mounted to a movable housing on the column to permit positioning the milling cutter forward or rearward in a horizontal plane. Two popular ram-type milling machines are the universal milling machine and the swivel cutter head ram-type milling machine.
- *Floor Mill:* Like some other types of milling machine, this one has a spindle that runs on a set of tracks. The horizontal pendant spindle runs parallel to a row of rotary tables. Large and complex pieces of machining can take place on a floor mill due to the size and number of platforms.

The milling process can be divided into several strategies; General milling strategy; High Speed Machining (HSM); High Productivity Machining (HPM); High Feed Machining (HFM); Micro Milling. Each strategy has its own know how, including cutting process parameters, cutting tool geometry and requires specific machine tool characteristics. Understanding each milling strategy and possibilities will result in an optimization of the entire production system and in increasing the energy efficiency, leading to:

- Low production costs in terms of energy consumption.
- Minimum amount of cutting tools and removed material.
- Lower production times.

Cutting tool

Milling cutters are available in many standard and special types, forms, diameters, and widths. The teeth may be straight (parallel to the axis of rotation) or at a helix angle. The helix angle helps a slow engagement of the tool distributing the forces. The cutter may be right-hand (to turn clockwise) or left-hand (to turn counter clockwise). They are generally made from high speed steel which means they will cut through metals such as mild steel and aluminium.

Milling machine

The milling machine is one of the most versatile machine tools in existence. In addition to straight milling of flat and irregularly shaped surfaces, it can perform gear and thread cutting, drilling, boring and slotting operations, which are normally handled on machine tools designed for these specific operations. As seen before, the milling machine removes metal with a revolving cutting tool called a milling cutter. With various attachments, milling machines can be used for boring, slotting, circular milling, dividing, and drilling. Milling machines can also be used for cutting keyways, racks and gears and for fluting taps and reamers.

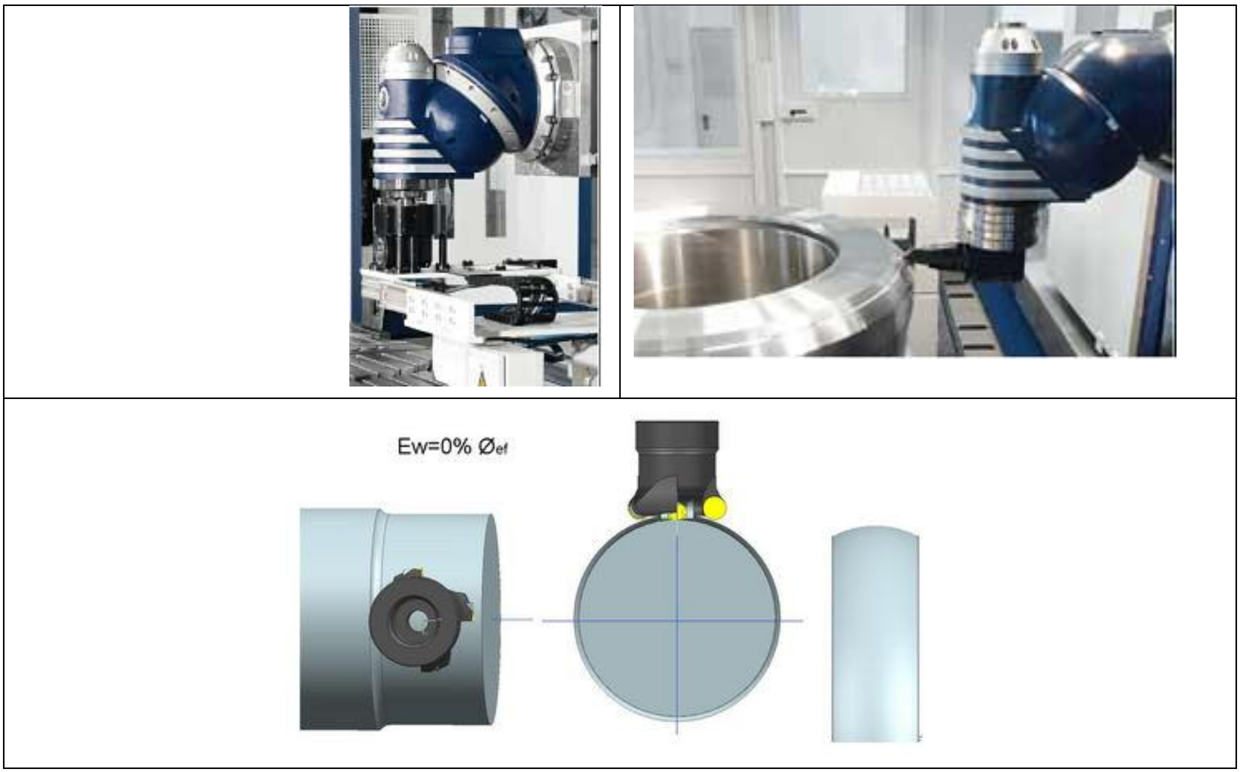


Figure 17: Flexible milling operation

Milling machines are classified as being horizontal or vertical to indicate the orientation of the spindle axis. These machines are also classified as knee-type, ram-type, manufacturing or bedtype, and planer-type milling machines. Most machines have self-contained electric drive motors, coolant systems, variable spindle speeds, and power operated table feeds.

Figure 18: Milling machine

Functional modules

Manufacturers are continuously striving to reduce cycle time, decrease cost, and improve performance. Manufacturing cost is traditionally thought of in terms of cycle time and resources (labor and material). Optimization in terms of machine selection, tooling, manufacturing operations, and component features is rarely performed from the energy efficiency perspective. The next generation of innovation will be driven by affordability and sustainability, not only as a plan to reduce costs and environmental impact, but as a business strategy to succeed.

Machine internal energy and machine external peripherals are important consumers and there are many studies that show that the major share of a machine tool’s energy consumption is load-independent and used by peripheral equipment. Assuming that the chip removing energy of a typical milling process has minor impact on the total energy consumption, the auxiliaries dominate the total energy consumption. From these findings, a comparison based on the chip-removal energy is not applicable.

Relevant direct value adding functions of the machine tool must be identified for all embracing energetic optimization, thus defining the favoured goal functionality such as chip removal or direct process cooling. Auxiliary components, often with a constant load and power consumption, fulfil essential functionality but without proportionality to added value. The goal is to define their share and amount in order to minimize the power consumption to the essential physical minimum. Furthermore, their functionality might be substituted by corresponding technologies or proper dimensions in order to increase energy efficiency.

2.2.2 Punching

Punching [13][14] is a metal forming process that uses a press to force a tool, called a punch, through a workpiece which is supported on the opposite side by a die, to create a hole via shearing. The punch is a protruding element and the die is usually a flat surface with various recessed areas for the protruding element to stamp. The die holes help to localize the shearing forces for a cleaner edge. The protruding element presses into the workpiece with many tons of pressure, removing a portion of the workpiece (called a slug) which usually falls through the recession in the die. There is a small amount of clearance between the punch and the die to prevent the punch from sticking in the die, and so less force is needed to make the hole. The amount of clearance needed depends on the thickness, with thicker materials requiring more clearance. The clearance is also dependent on the hardness of the workpiece. Depending on the material being punched the scrap slug may be recycled and reused or discarded. The whole process can take less than a second. Punching is often the cheapest method for creating holes in sheet metal in medium to high production volumes. The illustration that follows provides a look at a typical punching process. Note how the workpiece remains and the punched part falls out as scrap as the punch enters the die.

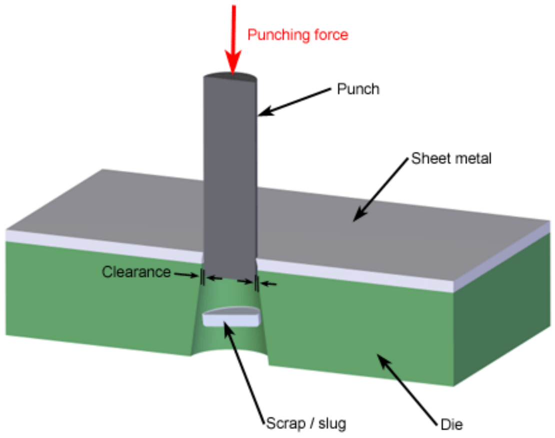


Figure 19: Typical punching operation

The workpiece is often in the form of a sheet or roll. Materials for the workpiece can vary, commonly being metals and plastics. Punch tooling (punch and die) is usually made of hardened steel or tungsten carbide.

Often, there is a very high cost for creating a punch and die setup, although the rewards of such a system is that the cost per piece is significantly less than any other method after the setup has been created. While a punching operation is ideal for high production runs, it is usually difficult to justify the cost of a stamping setup without high volume production.

When the cost of making a punching operation is not justifiable, manufacturers can turn to a process called CNC turret punching [15]. CNC turret punching creates shapes in sheet material by successively punching a series of basic shapes such as circles and rectangles. The machine houses punches and their corresponding dies in a revolving index. The turret feeds the correct punch and dies into the punching center of the machine. Then, the machine receives commands from the computer in order to punch single holes in the locations specified by the computer program. Whereas the stamping press can create a part in a single hit, the CNC punch press creates a part with multiple hits very quickly. CNC punching machines can punch a hole in half a second or less. While the creation of the parts takes longer, there is no need for an expensive punch and die system to be made.

The punch and die themselves can have a variety of shapes to create an array of different shaped holes in the workpiece. The illustration that follows shows a few common punch-and-die configurations and the workpieces that would be formed by this combination.

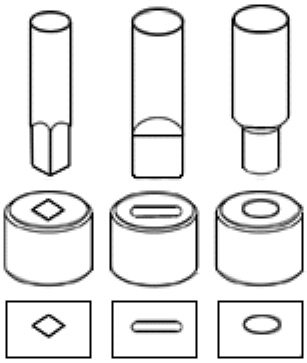


Figure 20: Common punch-and-die configurations

Most punch presses are mechanically operated, but simple punches are often hand-powered. CNC turret punches use hydraulic, pneumatic, or electrical power to press the shape with enough force to shear the metal.

The punch force required to punch a piece of sheet metal can be roughly estimated from the following equation:

$F = 0.7*t*L*(UTS)$ (9)

Where t is the sheet metal thickness, L is the total length sheared (perimeter of the shape), and UTS is the ultimate tensile strength of the material.

The above equation just provides an estimation of the force needed to punch a sheet of metal for more accurate calculations we must define the type of punching. Punching can be done without shear or with shear.

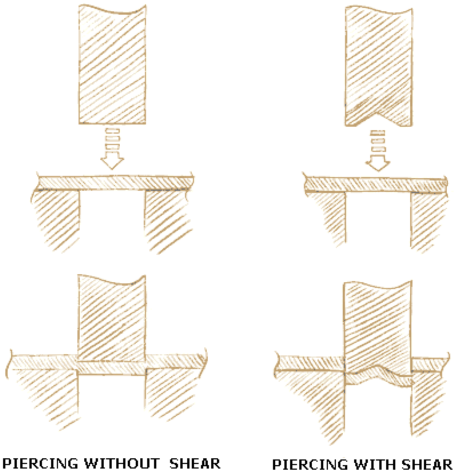


Figure 21: Punching with and without shear

- *Punching without shear [16]*: This is the case where the entire punch surface strikes the material square, and the complete shear is done along the entire cutting edge of the punch at the same time.

  $F = t*L*(UTS)$ (10)

  Where t is the sheet metal thickness, L is the total length sheared (perimeter of the shape), and UTS is the ultimate tensile strength of the material.

- *Punching with shear [16]*: This is the case where the punch surface penetrates the material in the middle, or at the corners, first, and as the punch descends the rest of the cutting edges contact the material and shear the material. The distance between the first contact of the punch with the material, to when the whole punch starts cutting, is the Shear Depth. Since the material is cut gradually (not all at the same time initially), the tonnage requirement is reduced considerably. The Punching Force calculated above is multiplied by a shear factor, which ranges in value from 0.5 to 0.9 depending on the material, thickness, and shear depth.

  $F = k*t*L*(UTS)$ (11)

  Where t is the sheet metal thickness, L is the total length sheared (perimeter of the shape), UTS is the ultimate tensile strength of the material and k is the shear factor (0.5-0.9)

It is obvious that the energy needed to punch a hole of a given diameter to a given material can be easily calculated. This is the “useful energy” *Eu*.

The main component to a punching machine is the press. Presses fall into four main categories—mechanical, hydraulic, servo, and pneumatic [17][18]. Most punch presses today are hydraulically powered. In older machines however, power is provided by a heavy, constantly-rotating flywheel. In the modern workplace, the flywheel is powered by a large electric motor.

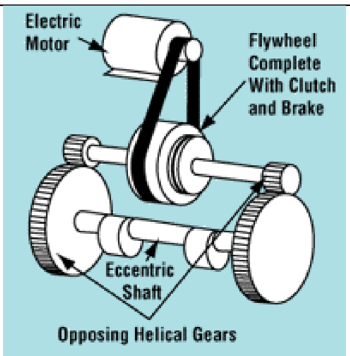


Figure 22: Typical mechanical punch press mechanism

Mechanical presses range in size from 20 tons up to 6000 tons. Strokes range from 5 to 500 mm and speeds from 20 to 1500 strokes per minute.

Hydraulic punch presses use hydraulics to deliver a controlled force. Tonnage can vary from 20 tons to 10,000 tons. Hydraulic presses can deliver the full power at any point in the stroke; variable tonnage with overload protection; and adjustable stroke and speed.

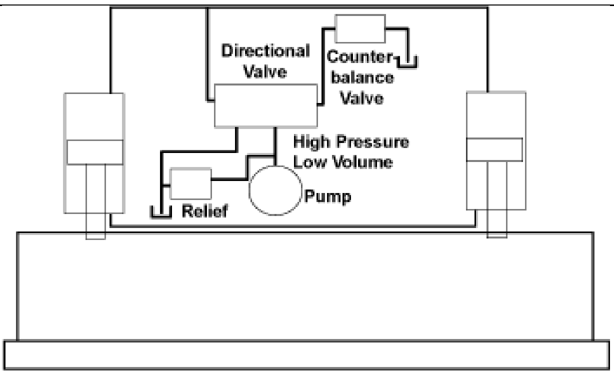


Figure 23: Punching force is created by applying pressure through hydraulic fluid to the area of the cylinder

Pneumatic presses operate in the same manner as hydraulic ones, but they are feed through compressed air lines, often via a central compressor used to power other machines too.

Servo drive turret punch press uses twin AC servo drives directly coupled to the drive shaft. This drive system combines the simplicity of the original clutch and brake technology with the speed of the hydraulic ram driven systems. This results in high performance, reliability, and lower operating costs. Servo drive press system doesn't have complex hydraulics and oil-cooling chillers reducing maintenance and repair costs. Turret press can be equipped with an advanced technology that stores and reuses energy generated during ram deceleration, providing extended electrical power savings.

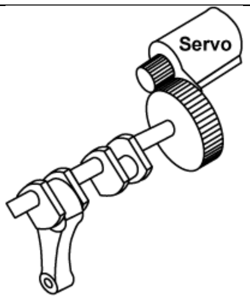


Figure 24: Servo presses use a direct-acting motor to drive the shaft; however, unlike on standard motors, the motion can be stopped and reversed.

The input in such a process is energy, and the output a punched part. With a given hole geometry (size and shape) and a constant material (thickness and properties), the exact amount of energy needed to create the hole can be calculated. Therefore the energy efficiency is defined as:

$$Eef = \frac{Eu}{Ein} \qquad (12)$$

where E_u is the energy needed to punch a hole of a given diameter to a given material and Ein is the input energy.

In general punching processes are very energy efficient, compared to alternatives such as laser cutting and milling. Due to multiple holes created in a single operation, energy efficiency is even higher. Even in CNC turret punch presses, which punch only one (or a few) holes at the time, energy efficiency is high due to rapid production of parts. Losses on such machines are in the form of heat produced by the rapid plastic deformation of the material when it is sheared, and by frictional losses in gears, slides and eccentric shafts.

A further reduction in efficiency comes from the fact that the power sources for the machines have fairly limited efficiency; electric motors, servos, compressors and pumps have efficiency below 100%. Moreover, hydraulic and mostly pneumatic systems are prone to leakages. Pneumatic systems also require filters and air dryers, which consume additional energy. As presses need to exceed maximum force only at a limited portion of their movement, KERS (Kinetic Energy Recovery Systems) have lately been incorporated in such machines in order to increase their efficiency by storing energy when braking and using it to the next work stroke.

In general, AC induction motors operate in efficiencies ranging from 70 to 90%, and most efficiently at around 75% of full rated load, as seen on the figure 25 below [19]. At roughly 40% of full load, a motor's efficiency begins to decrease, and at even lower loads the efficiency drops off precipitously.

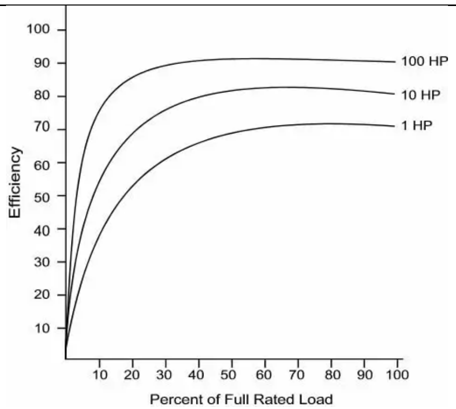


Figure 25: Typical efficiency graphs for various AC motor sizes

The approximate total system efficiency for a hydraulic system consisting of cylinders and pumps (without including the pressure drop in the hydraulic pipes and valves) is about 75%. Cylinders normally have a total efficiency around 95% while hydraulic axial piston motors 87%, the same as the pumps. We can safely assume that pneumatic system efficiency is even lower due to leakages.

Having in mind the above facts, any efficiency improvements on the punching processes should come from:

- An improvement of the power source efficiency (AC electric motors/Servo motors/Pumps/Compressors).
- A reduction of frictional losses.
- Regeneration of kinetic energy to use it on the next stroke
- Regeneration of the heat produced during punching to heat water or to create electricity.

Due to the fact that press motors are variably loaded (heavily loaded only for a small portion of their working cycle), intelligent electric motor management systems can save significant amount of energy. A case study by Power Efficiency Corporation on a 10hp stamping press [20] led to a 23.58% power savings, lowering the average kW usage from 3.52kW to 2.69kW by using the company’s E-Save Technology.

2.2.3 Forming (press)

Forming technologies are widely spread in all manufacturing sectors. Metal forming processes transform a simple-geometry blank into a complex-geometry product through the plastic deformation of the metal in open or closed dies. The deformation can require a single stage operation where every stroke of the press produces the desired form on the sheet metal part, or multiple stages to obtain the net shape desired geometry.

Due to the high cost of the dies these processes are primarily reserved for mass production. Metals to be formed must be ductile and have low yield strength. An important role to enhance these properties can be played by temperature, by preheating the blank prior to its placement in the press. Furthermore, one should note that metal forming processes may take one or a few iterations (i.e., using one or multiple dies) in yielding near net shape desired geometries with no or little scrap.

Deformation of a solid body can be classified as elastic or plastic: when unloaded, an elastically deformed body always returns to its original shape regardless of history, rate, time, and path of loading; the plastic deformation of a body, on the other hand, depends on all these variables and is subjected to (permanent) loss of original shape when unloaded. Although the theory of elasticity is well established and yields accurate predictions of strain (due to mechanical stress), the theory of plasticity normally drive to approximate solutions to plastic deformation problems. The typical one-dimensional stress–strain curve is shown in the figure below.

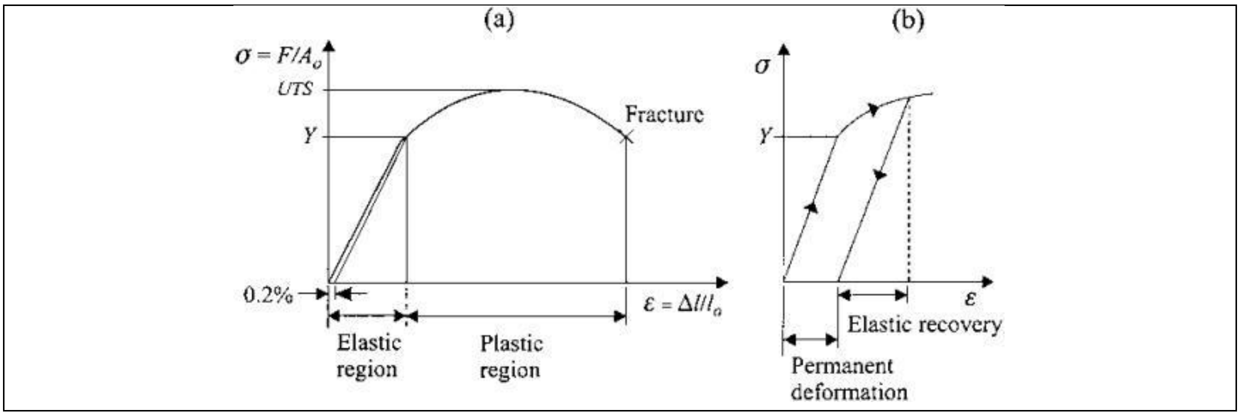


Figure 26: typical one-dimensional stress–strain curves displaying elastic and plastic regions.

As mentioned above, in metal forming the preference would be to process materials whose ductility is high (and that could be made even higher by increasing the temperature). Another important factor in metal forming is the rate of deformation (i.e., the amount of strain per unit time). It has been accepted that as the rate of deformation is increased, so would the necessary amount of stress to induce the required strain rate. As the temperature of the part is increased, however, one can obtain higher rates of deformation. Thus an increase in temperature raises ductility, lowers yield point, and thus shortens forming cycle times.

Common sheet metal forming processes

Within the ENEPLAN project we are interested in Sheet Metal Forming; for this reason, from now on we will refer to Sheet Metal Forming as forming in general. In sheet metal forming, a sheet blank is deformed into a three dimensional object. The main advantages of metal forming are the following:

- High productivity
- Low cost per part
- Low scrap material and energy consumption
- Quality of formed parts.

Forming processes strictly related to sheet metal forming are the following.

- *Rolling:* Long parts with constant complex cross-sections; good surface finish; high production rates; high tooling costs

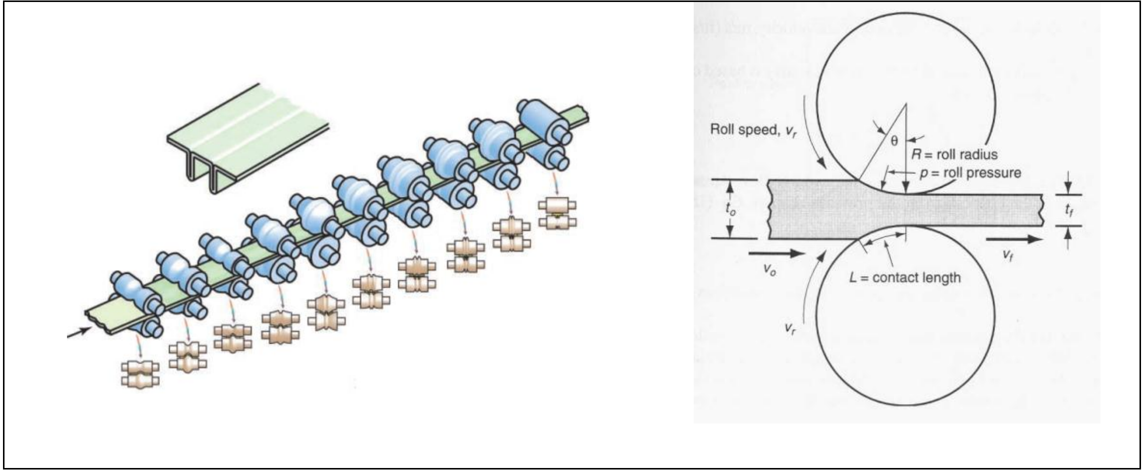


Figure 27: Rolling process

- *Forging:* The origins of this forming process may be traced to the ancient process of hammering of gold foil, between a rock, the anvil, and a stone, the hammer. Basically it involves plastic deformation of material between two dies to achieve desired configuration. Depending upon complexity of the part forging is carried out as open die forging and closed die forging.

- *Bending:* A metal forming process in which a force is applied to a sheet metal, causing it to bend at an angle and form the desired shape. Generally, a bending operation causes deformation along one axis, but a complex part can be created with a sequence of several different operations. Bent parts can be quite small, such as a bracket, or up to 20 feet in length, such as a large enclosure or chassis. A bend can be characterized by several different parameters, shown in the image below.

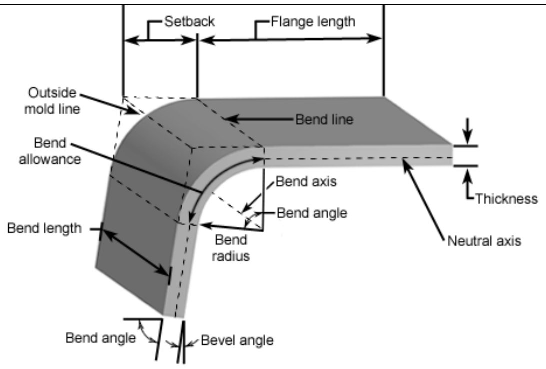


Figure 28: The bending process [21]

- *Extrusion:* See dedicated section 2.3.1
- *Drawing/ Deep drawing:* A cold working process which is widely used to fabricate large quantities of wires, rods, tubes and other sections. In this process the material is pulled through a die in order to reduce it to the desired shape and size. The main features of this process are:
    - Shallow or deep parts with relatively simple shapes;
    - high production rates;
    - high tooling and equipment costs;
    - good surface final and dimensional accuracy;
- *Deep drawing:* A metal forming process in which a metal sheet is drawn under an action of a punch which forces the metal within the mold cavity. This process can be applied to very ductile sheet metal, and it is different from other processes as it can reaches a major drawing depth in comparison to the initial radius of the sheet (the ratio between the initial sheet radius and the radius of the can to be formed is called “drawing ratio”) and allows to fabricate a wide range of geometric shapes.
- *Shearing processes:* (e.g. punching, blanking, piercing), see dedicated section 2.2.2

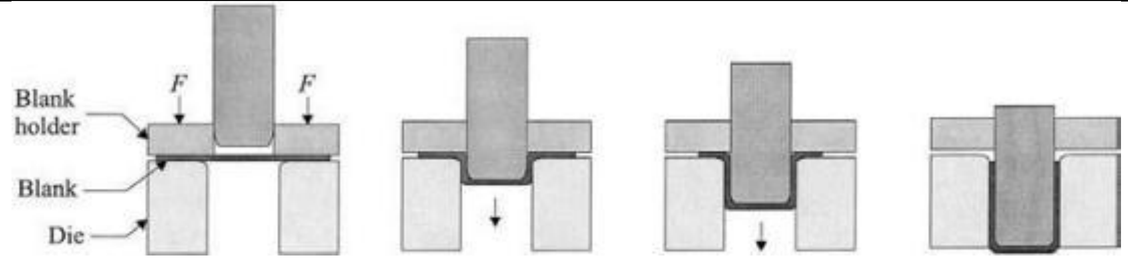


Figure 29: The deep drawing process

Simulation of forming processes

In the sheet metal forming processes there is still a lack of knowledge in modelling. Not a long time ago, the design of metal forming tools was based mostly on experience. Today finite element based methods are largely used, even in the early phases of the design in order to obtain information on the manufacturability of the sheet metal part and to optimize the tool design. Many commercial programs are widespread today, and they differ also in theories underlying them and, thus, in the quality of the results. Moreover the simulation is no longer focused only on verification of feasibility, but it focuses also on the optimization of the first forming stage. By using simulation tools, large savings have been achieved and can still be achieved in terms of a more rapid development of tools and a shortening of validation/trial processes. In the following table an overview of the actual simulation models is given.

Factor to be considered	Reality	Simulation
Tools	Elastic behavior	Rigid behavior
Friction coefficient	Not constant	Constant
Material	Complex model	Simplified models
Material properties	Not constant	Constant (most of them)
Temperature	Not constant	Non in the model

Table 2: Overview of the actual simulation models

Before 1960 simulation procedures were predominantly empirical and theoretical simulation methods were based on the elementary plasticity theory. Nowadays the approaches of higher plasticity theory is available, therefore it has been possible to reformulate numerical methods so that they can be easily executed on the computer. It was soon clear that simple models such as Tresca and von Mises were inadequate to describe the material behavior. Moreover models need to be able to describe anisotropy, kinematic hardening and so on and the tensile stress test is no longer sufficient to characterize the material characteristics. Until now, even in expanded models the material is considered to act as an incompressible body during plastic deformation. This assumption does not fit with HSS and AHSS, so it represents a development focal point in simulation tools.

Another fundamental aspect of forming is the spingback phenomenon. It is related both to the E-module and the yield stress of the material. The E-module changes during forming and its changes during the plastic deformation plays a significant role for the springback simulation. Another current problem, especially for the deep drawing process, is the approximation of flow stress. In deep drawing it occurs in higher degrees of freedom that for example in standard tensile stress. Flow curves are experimentally extrapolated, and they can largely affect accuracy of the springback. If an accurate simulation is to be obtained, also anisotropy must be taken into account. Usually we refer to a vertical anisotropic value that has to be measured which describes the relationship between forming along the thickness and forming in the plane of the sheet. This parameter can also change during plastic deformation, so it is another factor that has to be taken into account in order to obtain an accurate simulation. In general friction it is assumed to be constant and is usually described by a friction coefficient, but in reality it is influenced by several factors. A small change in this parameter can strongly affect the springback, so new contact models must be developed. This aspect is also related to the modeling of tools properties. As stated above, tools are considered to be rigid. Especially for what concerning HSS and AHSS, this assumption is no longer acceptable and elastic properties of tools must be included.

As already mentioned, in the automotive industry steel with enhanced strength are more and more used; since hot forming process are applied, to perform an accurate calculation of the temperature distribution is a key-factor in the simulation of the process.

Innovative materials

As there is a high emphasis on emissions reductions and improving fuel efficiency in the transportation sector, a focal point in the research of forming processes is represented by lightweight materials. To achieve lightweight construction, it has been investigating the replacement of steel with aluminium, magnesium, composites, and foams. The recycling and recovery of end-of-life vehicles, which involves recovery targets of 85%, are driving the auto industry to adopt these materials to meet these targets.

Environmental sustainability in manufacturing is nowadays a crucial issue and the main priorities are efficiency (e.g. material use) and energy consumption. Moreover, industries are focused on sustainability also from an economic point of view related to the increase of raw material prices and environmental legislation. The recycling and recovery of end-of-life vehicles, which involves recovery targets of 85%, make these aspects very crucial even for the automotive industry [22]. For example, aluminum can add 6 to 8 percent fuel savings for every 10 percent weight reduction, save a net 20 pounds of carbon dioxide equivalents over the lifetime of the vehicle for every two pounds of steel replaced and allows for recycling (90% of aluminum is recovered or recycled). For these reasons materials play an important role in the process especially in terms of weight reduction. Of course, the applicability of such materials depends on cost effectiveness as well as on the possibility to apply forming processes on them. Metal families that are interesting in metal forming are steels (also HSS and AHSS), aluminium alloys, magnesium alloys and titanium alloys.

Parameters of main material families (ref. Kleiner et al., 2006)	Al	Mg	Steel	Ti
Density (kg dm^{-3})	2.8	1.74	7.83	4.5
Young modulus (GPa)	70	45	210	110
Tensile strength (MPa)	150-680	100-380	300-1200	910-1190
Specific strength = tensile strength/density (10^{6} Nmm kg^{-1})	52-243	57-218	38-153	202-264

Table 3: Average parameters for indicative material families

In addition to the average materials parameters of this table above, formability has to be investigated and the actual weight reduction potential can only be evaluate by referring to a specific component, due to the complex relationship between different parameters. Aluminum and Magnesium alloy sheets have limited formability and are difficult to form at room temperature but the formability considerably increases if they are formed at elevated temperatures, i.e., around 200-250°C. Aluminum sheets are increasingly used in forming operations because of its low weight and potential energy savings. The formability of aluminum is about two third of a deep drawing steel and its low Young’s modulus results in early wrinkling and spring back. Magnesium sheet has been used in automotive applications only in a few cases. The trend to increase strength in respect to weight ratios opens new possibilities for using magnesium.

Innovative forming technologies

Hydroforming: A weight reduction can also be achieved by the means of innovative technologies which drive to a reduction of number of components and which allow the means of joining technologies such as laser welding. The main principle of hydroforming is to deform tubes, sections or sheet within a mold by using the pressure of a liquid (for example water) which acts like a female die directly on the blank to be shaped. The surfaces of the mold cavity have the only function to contain the blank deformation caused by the liquid pressure. We can distinguish between two type of hydroforming depending on the level of pressure used: high pressure and low pressure processes. We can easily get that higher pressure are used for more complex geometry.

Hydroforming drives to higher costs than conventional forming techniques, but it allows realizing complex shape that would require more than one forming steps and final assembly, in a single operation. It is possible to eliminate joint and flanges. By the means of hydroforming, it is possible to obtain changes in section along the component if the thickness is not so high.

To summarize, main advantages of sheet hydroforming are the following:

- increased part accuracy
- increased surface finish
- uniform wall thickness
- complicated shapes can be formed in fewer process steps
- reduced tooling cost (up to 75%, considering number, maintenance and consumption)
- lower grade of blank material used
- process is suitable for low volume production.
- possibility of weight reduction (less components, less joints)

We can include in the main disadvantages:

- low cycle time and necessity to optimize the process (increasing pressure law)
- applicability to small batches
- high tooling time

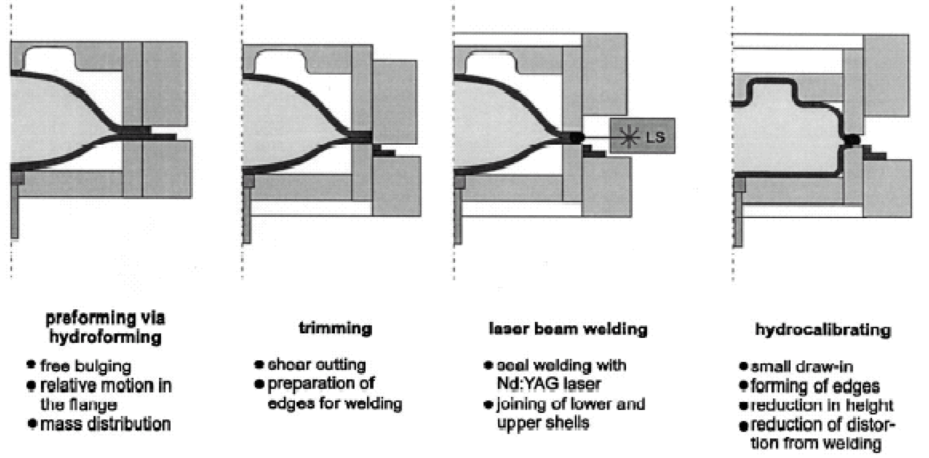


Figure 30: The hydroforming process

Incremental forming: The recent diversification of customer demand in the field of sheet metal forming led to the development of new manufacturing methods highly flexible and dedicated to the production of small batches. In the incremental forming process, a tool of a simple shape, driven by a CNC machine, locally impose a plastic deformation to the blank sheet in a progressive way.

One of the main advantages of this technique is the possibility to realize different geometries by the means of the same tool, simply setting the path of the tool for that specific geometry to be realized. Specific tools can be required only in case of a more complex geometry. Moreover the formability of sheet metal turns out to be higher than in conventional process, thanks to the progression of the forming action. On the other hand, the process turns out to be slower than conventional process and the knowledge about the incremental forming are still quite low.

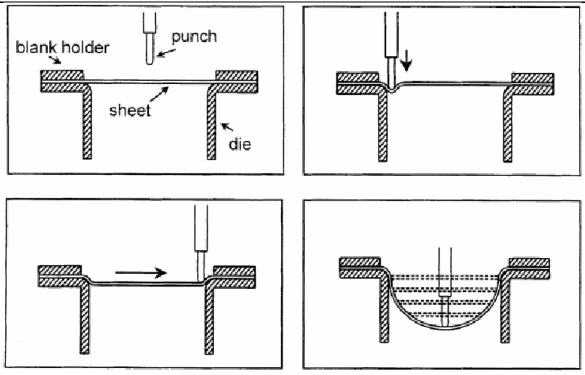


Figure 31: Incremental forming

Hot forming: In the last decays industry, in particular automotive industry focused its attention on material with lightweight potential such as Aluminium and Magnesium alloys and HSS. As already mentioned for Aluminium and Magnesium alloys, if there is an increase of the temperature in the forming process, an increase of formability of the material may occur because by lower forces are needed.

Forming presses

Forming processes are carried out by the usage of presses. A press is a sheet metal working tool with a stationary bed and a powered ram can be driven towards the bed or away from the bed to apply force or required pressure for various metal forming operations. A lot of different classifications exist according to the power source, the mechanism used to transmit the power to the ram, the purpose and so on. In any case we may distinguish between mechanical and hydraulics presses basing on the way of generating the force. Later on we will introduce servo drive presses to this list.

In mechanical presses the motion of the ram is obtained by the means of mechanism such as crank, linkage, knuckle-joint or screw press. The motion of the slide in hydraulic press is, instead, governed by a liquid pressure.

In general:

- Depending on the application, a hydraulic press may cost less than an equivalent mechanical press;
- Hydraulic presses have full force through the stroke, while mechanical presses have limited tonnage (related to energy stored in the flywheel) at limited stroke (near the bottom position of the press stroke);
- Hydraulic presses are more flexible in terms of velocity regulation: hydraulic machines can be made with fully programmable control over ram speed and ram position, which is not possible in the mechanical press.
- Mechanical presses can operate at higher velocity (lower cycle time)
- Mechanical presses best fit with high production volume

Recently several press builders, especially in Japan and Germany, developed mechanical servo-drive presses which offer the flexibility proper of hydraulics presses and the main advantages of a mechanical presses (such as speed, accuracy and reliability). Until the middle of 20th century, the power of servo-motor was not high enough to be used on metal forming machines. Servo-drive presses became to be fabricated after 1980; a 100kN bending machine was developed in 1987 and it can be considered the first commercial example of this kind of machine.

An important feature of servo drive presses is the possibility to store energy produced during the deceleration of the slide. In conventional mechanical presses the energy is stored in the flywheel, while in the hydraulic one the energy is lost. For servo drive presses, currently there are two options: to store the energy in the flywheel or to fed back to the network by using capacitors. Recent new technologies in the form of servo-driven presses, or servo presses, to metal stampers are emerged. Servo presses, though technically classified as mechanical presses, employ servo drives to provide power, negating the need for flywheels. Advantages of servo presses include the ability to control the stamping press' stroke length and velocity. Another plus: Servo presses allow for dwell time at the bottom of a press stroke, where forming work occurs. This is ideal when material must be given time to flow or stretch into a part shape. Features such as these bring benefits of mechanical and hydraulic presses into a single machine, providing flexibility to the stamper.

Application of servo drive presses can be found in bending, deep drawing, deep drawing with heated tool, shearing and hot forming. In this last example, the use of a mechanical servo press is very advantageous to prevent temperature drop thanks to its high slide speed.

2.3 NON-CONVENTIONAL MACHINING PROCESSES

2.3.1 Extrusion

Metal extrusion was developed in the late 18th century for making lead pipe. The basic process of forcing a round billet through a shaped die is still used today. Extrusion is a process used to create objects of a fixed cross-sectional profile from straight metal parts. A material is pushed or drawn through a die of the desired cross-section. The materials that are mainly used are softer metals (e.g. aluminium, copper, zinc.). The cross-sections that can be produced vary from solid round, rectangular, to L shapes, T shapes, tubes and many other different types. Extrusion is done by squeezing metal in a closed cavity through a tool, known as a die using either a mechanical or hydraulic presses. Typical parts produced by extrusions are trim parts used in automotive and construction applications, window frame members, railings, aircraft structural parts.

Extrusion produces compressive and shear forces in the stock. No tensile forces are produced, which makes high deformation possible without tearing the metal. The cavity in which the raw material is contained is lined with a wear resistant material. This can withstand the high radial loads that are created when the material is pushed the die . The main advantages of this process over others are its ability to create very complex cross-sections and work materials that are brittle, because the material only encounters compressive and shear stresses. It also forms finished parts with an excellent surface finish [23]. In general, the softer the metal is the more intricate the shapes that can be made. Extrusions, often minimize the need for secondary machining, but are not of the same dimensional accuracy or surface finish as machined parts. Typical surface finish for steel is 3 µm and 0.8 µm for aluminum and magnesium; however this process can produce a wide variety of cross-sections that are hard to produce cost-effectively using other methods. Minimum thickness of steel is about 3 mm (0.120 in), whereas for aluminum and magnesium is about 1mm (0.040 in). Minimum cross sections are 250 mm2 (0.4 in2) for steel and less than that for aluminum and magnesium. Minimum corner and fillet radii are 0.4 mm (0.015 in) for aluminum and magnesium, and for steel, the minimum corner radius is 0.8mm (0.030 in) and 4 mm (0.120 in) fillet radius.

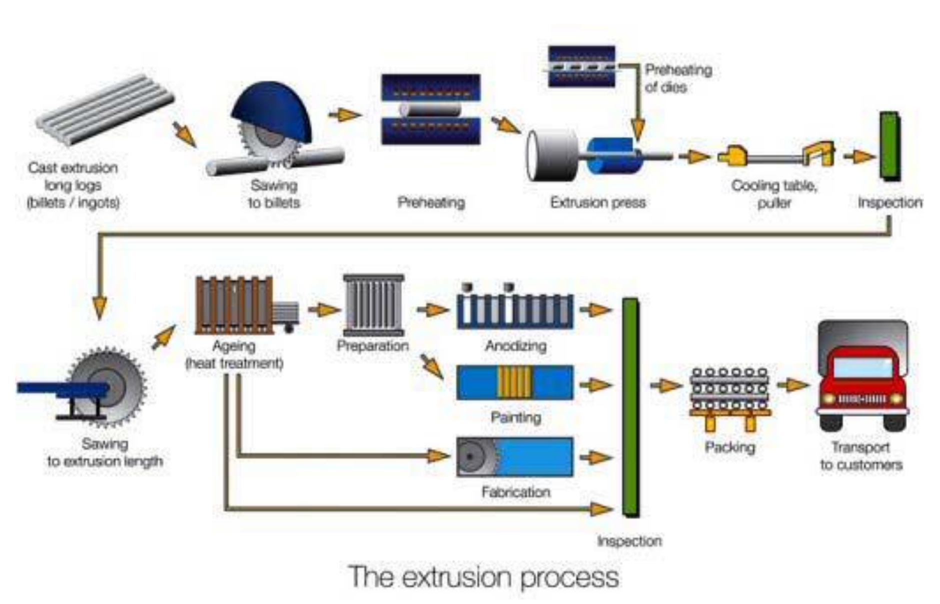


Figure 32: The principle of the extrusion process [24]

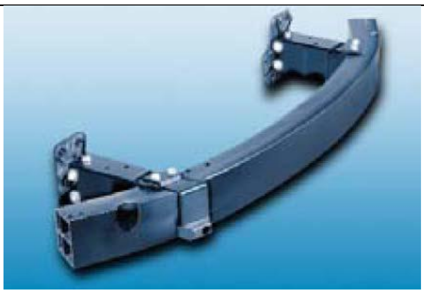


Figure 33: Bumper system made of aluminium extrusions [25]

Although extrusion appears to be a continuous process, it is really a batch process as it needs to be interrupted to load new billets. The extrusion process is generally economical when producing between several kilograms (pounds) and many tons, depending on the material being extruded. There is a crossover point where roll forming becomes more economical. For instance, some steels become more economical to roll if producing more than 20,000 kg (50,000 lb) [26]. Some typical prices may be the following [27]:

- Typical machine prices: over 65,000 €
- Dies to be produced (without considering the design): over 1300 €
- Typical production time 5-10metres/minute (needs several thousand meters to be economic)

Hot Extrusion

Figure 34: Hot extrusion process

Hot extrusion is a hot working process (approximately 50 to 75 % of the melting point of the metal), which means it is done above the material's re-crystallization temperature to keep the material from work hardening and to make it easier to push the material through the die. Most hot extrusions are done on horizontal hydraulic presses that range from 230 to 11,000 metric tons (250 to 12,000 short tons). Pressures range from 30 to 700 MPa (4,400 to 100,000 psi), therefore lubrication is required, which can be oil or graphite for lower temperature extrusions, or glass powder for higher temperature extrusions. The biggest disadvantage of this process is its cost for machinery and its upkeep [23]. In addition to this, dimensional tolerance and surface finish may be poor with hot extrusion.

Material	Temperature [^{o}C]
Magnesium	350-450
Aluminium	350-500
Copper	600-1100
Steel	1200-1300
Titanium	700-1200
Nickel	1000-1200
Refractory alloys	Up to 2000

Table 4: Hot extrusion temperature for various metals [23]

Cold Extrusion

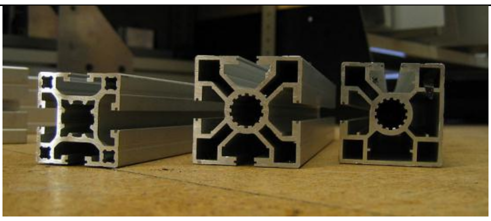


Figure 35: Extruded aluminium section

Cold extrusion is done at room temperature or slightly elevated temperatures. Cold extrusion is possible for some metals giving better properties. The advantages of this over hot extrusion are the lack of oxidation, higher strength due to cold working, closer tolerances, good mechanical properties due to severe cold working as long as the temperatures created are below the re-crystallization temperature, good surface finish with the use of proper lubricants, and fast extrusion speeds if the material is subject to hot shortness [23]. Materials that are commonly cold extruded include: lead, tin, aluminum alloys, copper, titanium, molybdenum, vanadium, steel. Examples of parts that are cold extruded are collapsible tubes, aluminum cans, cylinders, gear blanks.

Warm extrusion

Warm extrusion is done above room temperature, but below the re-crystallization temperature of the material the temperatures ranges from 800 to 1800 °F (424 to 975 °C). It is usually used to achieve the proper balance of required forces, ductility and final extrusion properties [28].

Energy optimization factors

Analyses of energy consumption in manufacturing processes have shown that most of the energy is needed for the production of material such as aluminum or steel and not for further manufacturing steps like forming or cutting. A global reduction of CO2 emissions is becoming more and more important to prevent global warming caused by greenhouse gas production [29]. Due to this, the need for a decrease in energy consumption in every field of industrial processes as well as transportation and production engineering is a major factor in today’s industrial world. In the area of cutting and forming technology, typically, the major amount of energy is not used for the manufacturing process, but for the production of the primary material, made from first melting after mining, or secondary material, made from melting after recycling. In case of cold or hot extrusion of steel, approximately 90–93% of the energy used is needed for the material production, 3% for thermal treatment, and only 1% for the forming process [30]. Due to the energy consuming electrolytic production of aluminum, the amount of energy needed for the production process is even larger. These facts indicate, that from an economic and ecologic point of view reducing the production of primary material the most efficient way to reduce energy consumption and, thus, CO2 production. In order to achieve that a reduction of the amount of primary material, made from first melting after mining, as well as secondary material, made from melting of recycled scrap material, is needed. On the other hand, another meaningful factor in a forming operation is the exact determination of the pressure (die profile optimization etc).

A number of studies on plane-strain and axisymmetric extrusion using symmetric and asymmetric dies have been carried out by many researchers and a list of references on this topic is given by Johnson and Kudo [31]. In general, different arbitrary curved die profiles have been proposed by some researchers [32][33][34][35][36][37].

It is difficult, by means of analytic models, to determine the force of extrusion process exactly. Therefore, stochastic models especially provide wider possibilities in the solving of extrusion force [38]. It is useful to perform the stochastic modeling of the backward extrusion process before expensive manufacturing process. In this way, savings in process and tool improvements can be made at the start stage of process, before its establishing. When the parameters of process became better-understood, extrusion force by means of stochastic modeling can be determined.

Automotive case study on extrusion

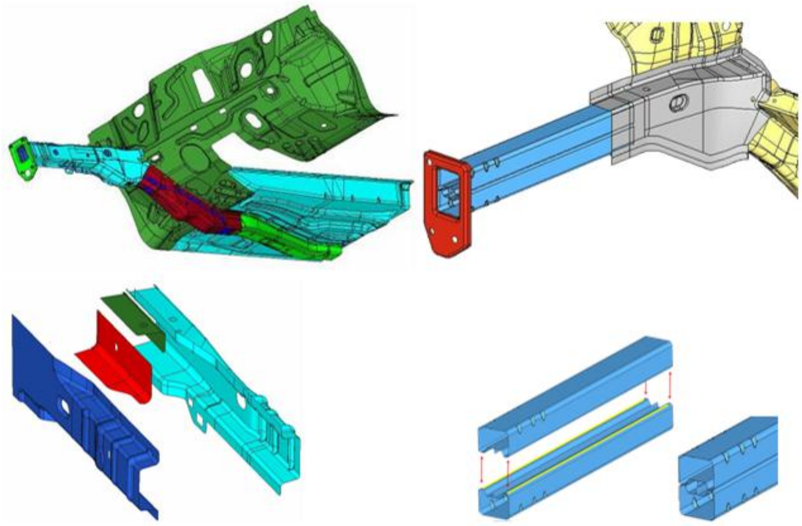


Figure 36: A concept of replacing a frontal area of the stamped front side rail with an extruded adapter made of advanced aluminium alloy [39].

Weight reduction achieved from 8.01 kg per part (stamping solution) to 6.93 kg (extruded adapter solution). In addition to this, in order to produce 60.000 parts/year the cost per rails drops from 16.45 € to 10.80 € [39].

2.3.2 Laser machining

Laser (light amplification by stimulated emission of radiation) is a coherent and amplified beam of electromagnetic radiation. The key element in making a practical laser is the light amplification achieved by stimulated emission due to the incident photons of high energy in the laser source:

- The carbon dioxide laser (CO_2 laser) was one of the earliest gas lasers to be developed (invented by Kumar Patel of Bell Labs in 1964), and is still one of the most useful. Carbon dioxide lasers are the highest-power continuous wave lasers that are currently available. The CO_2 laser produces a beam of infrared light with the principal wavelength bands centering around 9.4 and 10.6 micrometers. The ratio of output power to pump power can be as large as 20%, with wall-plug efficiency up to 10%.
- A fiber laser is a laser in which the active gain medium is an optical fiber doped with rare-earth elements such as erbium, ytterbium, neodymium, dysprosium, praseodymium, and thulium. Fiber lasers can have active regions several kilometers long, and so can provide very high optical gain. They can support kilowatt levels of continuous output power because of the fiber's high surface area to volume ratio, which allows efficient cooling. They are compact in size, because the fiber can be bent and coiled to save space. Fiber lasers exhibit high vibrational stability, extended lifetime, and maintenance-free turnkey operation.

Over the last twenty years laser processing has become an increasingly indispensable part of competitive manufacturing throughout the world [40]. Various alterations of machining, welding, surface and heat treatments are carried out using mostly CO2, Nd:YAG or HPD laser beams. Several advantages provided by laser manufacturing explain this trend. Given that laser beams can be easily manipulated in space with optics provides the capability of processing a wide variety of part geometries and sizes, while achieving reasonable material processing rates. In combination with automatic workpiece positioning devices they provide very accurate and high speed processing [41] [42].

The laser is also used to perform turning as well as milling operations but major application of laser beam is mainly in cutting of metallic and non-metallic sheets. Laser sources can be operated in pulse mode, with a sequence of charge (off) state and emission (on) state (by an electro-optic switch or “Q-switch”), to limit heat propagation in the workpiece, realizing localized heat sources, with narrow Heat Affected Zones (HAZ) and low workpiece distortion. Since lasers are thermal in nature, they are particularly oriented for processing materials that are difficult to process with mechanical processing (e.g. ceramics, composites, hardened alloys) [41][42].

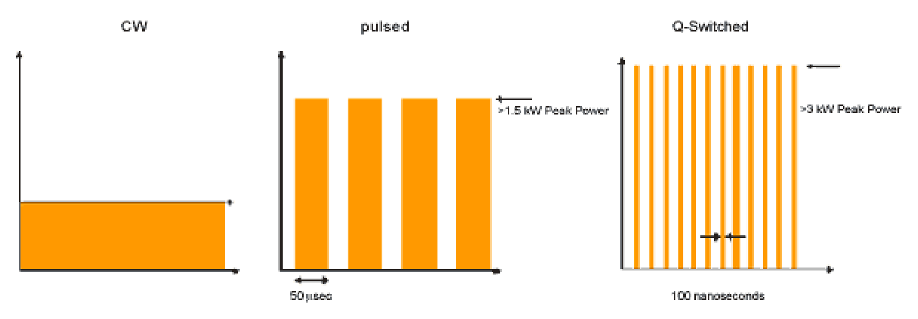


Figure 37: Laser source operational modes

A laser system comprises three principal components, namely, the lasing medium, means of exciting the lasing medium into its amplifying state (lasing energy source), and optical delivery/feedback system. Additional provisions of cooling the mirrors, guiding the beam and manipulating the target are also important. The laser medium may be a solid (e.g. Nd:YAG or neodymium doped yttrium– aluminum–garnet), liquid (dye) or gas (e.g. CO2, He, Ne).

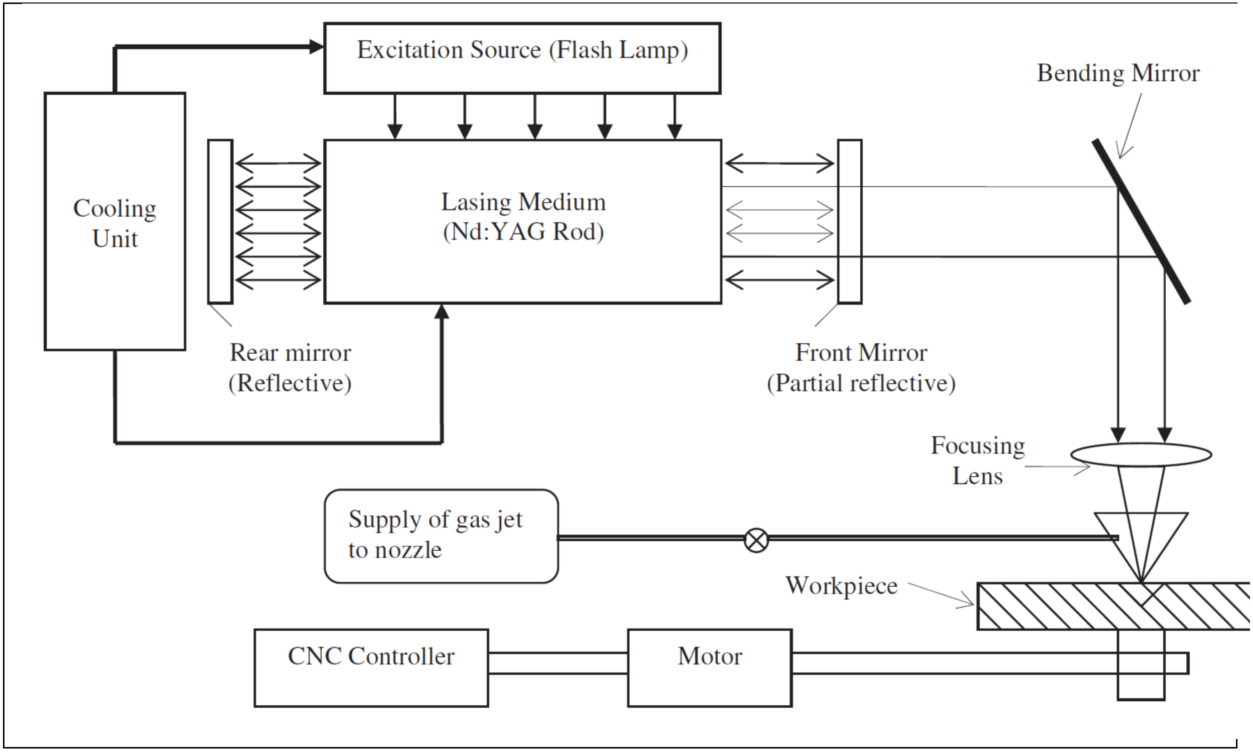


Figure 38: Laser Beam machining: main elements for energy consumption

The system elements to be considered for an environmental analysis, summarized in the previous figure, are:

1) *Laser source*: Its efficiency, expressed as ration between the emitted laser power and the input electrical power is quite low, strongly depending on the source typology.

Fiber lasers generate less heat and manage the heat more effectively. The quantum defect (that is the difference between pump and emission energy) is lesser for a Ytterbium diode pumped fiber laser (pumped at 980 nm) than a Nd:YAG diode pumped laser (pumped at 808 nm). Also, the optical to optical conversion efficiency of fiber laser is typically 70-80%, as compared with approximately 4% for lamp pumped YAGs, and approximately 40% for diode pumped YAGs and disk lasers. Because the light is always contained in a fiber, there are no additional sources of the loss inside the laser cavity. Typical overall efficiencies are from 6-8% for a CO_2 source, and up to 30% for a fiber source.

2) *The motion system*. It generates the relative motion between the laser beam and the work piece. It has architecture similar to that one of several machine tools (e.g. a milling machine) composed by structural elements, guide ways, kinematic chains, motors, drive and numerical control.
3) *The cooling system.* Given the high dissipated power in the laser source, the thermal efficiency of the cooling system can have a significant impact on the overall machine energy use, especially when operating in partial power modes.

Typically the dominating component of the energy use is due to the laser source, even if, obviously, it depends on the machining operation: simple motions at low speed with high source while cutting thick sheets, versus high speed motions at lower source power while cutting a thin sheet along complex trajectories.

To analyze the overall energy efficiency of the machine, also indirect effects must be taken into account:

1) *Beam quality:* fibre laser enables the beam to be focused to a small spot with a correspondingly high energy density. This enables very fast processing, yielding welds with a high aspect ratio. Compared with other laser sources, the fibre laser can produce welds with significantly lower heat input resulting in less distortion of the welded plates. The high energy stability, typically +/-0.5%, gives welds of consistent profile and penetration with extremely low levels of weld root porosity.
2) *The motion system:* It determines the processing time that influences the total energy consumption. Manufacturers continuously increase the motion system responsiveness, also adopting redundant kinematic schemes, also to keep the pace of the processing speed of the newest laser sources.
3) *Workpiece management in the machine automation*, that determines the unproductive time. (Some machines reduce this problem by working alternatively workpiece placed on two different tables).
4) *Laser source warm up time:* fiber lasers exhibit a much shorter warm up time and, therefore, can be switched off during part change or when the machine is waiting for a new piece. CO_2 lasers instead have typically a longer stabilization time.

The main laser disadvantage is the low energy efficiency of the process, since in order for the material to be removed by melting or vaporization relative high energy input is required [41]. There may be unnecessary energy use in the industrial sector in the order of 20-40% [42][43][44][45] and the large use of energy for industrial operations is mainly responsible for significant CO2 emissions and thus climate change [46]. The potential for energy savings in the machine tool sector is high (e.g. low power factor of 0.7-0.8), as the potential efficiency increase by exploiting Design for Environment strategies (e.g. reduction of mass, materials used, extension of tool lifetime, optimised PWB, CPU, monitor) [47].

As mentioned in [41] laser machining is a process with low energy efficiency. Energy efficiency however, has quickly become a top priority of both international and national policies. This is the main reason why methods that reduce the energy consumption and achieving better energy efficiency in manufacturing processes is very important. Energy efficiency has been addressed whereby the environment is regarded as thermodynamic systems [48][49][50][51]. The use of “exergy” premises the definition of the system’s inputs, outputs and borders [48]. It also influences both up and down the product life cycle [52]. In order both energy and “exergy” efficiency to be estimated, a method was proposed which is based on the balance of materials and energy [50].

In scientific literary, only few contributions regarding laser energy consumption and laser energy efficiency are present. Wang [53] presented rough estimations of the energy efficiency with respect to the various process parameters for CO2 laser cutting of metallic coated sheets steels. The author proposes a model in which the energy supplied to the cutting zone is taken as the sum of the energy used in cutting and the thermal losses by conduction, convection and radiation. Assuming that the energy to the surrounding (other than the processing) area by conduction, convention and radiation does not contribute to the cutting process and that the specific cutting energy for the work material remains constant, the energy efficiency has been determined with the following formulation:

$$Efficiency = \frac{Energy\ used\ for\ cutting}{Total\ laser\ energy\ input} \cdot 100\% = \frac{\rho \cdot V \cdot e \cdot k \cdot \left[c_p \cdot (T_m - T_r) + L\right]}{P} \cdot 100\% \qquad (13)$$

where:

- c_p is specific heat
- V is cutting speed
- e is material thickness
- k is kerf width
- ρ is material specific mass (mess density)
- T_m is melting temperature
- T_r is room temperature
- L is latent heat for melting
- P is laser power supply

The experimental analysis presented in [53] has shown that the energy efficiency ranges from as low as 5% to about 24% under the test conditions. High cutting speed and low laser power are favored from the energy efficiency point of view and this condition also gives small size of heat affected zone. It must be noted that in general laser process parameters are correlated each other and it is difficult to understand how the parameters have an impact on laser energy efficiency and on global energy consumption.

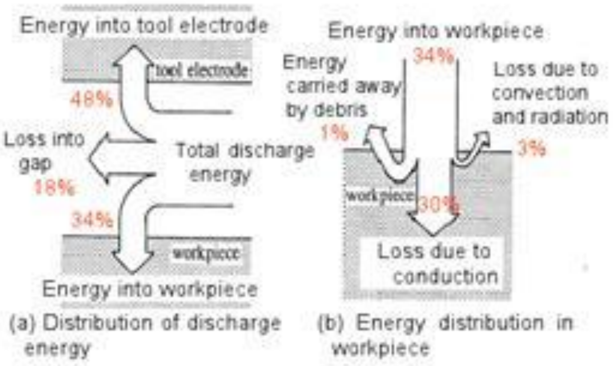
Thawari et al. [54] investigated the interaction of pulsing energy as a function of different laser parameters, for a laser cutting machining process. Zeng et al. investigated the minimum specific energy required for continuous laser cladding track, and linked it not only to the physical and chemical properties and size of the substrate material, but also to the thickness and physical and chemical properties of the cladding material. Coelcho et al. experimentally studied the welding of white and transparent thin films of polypropylene and polyethylene of low and high density at high speeds of 20 [m/s] using a CO^2 laser and presented results about the specific energy required [55]. Fysikopoulos et al. [56] have presented a first attempt in quantifying the energy efficiency the energy efficiency of laser drilling and laser grooving process.

2.3.3 EDM & Water Jet

Abrasive Waterjet Machining (AWJM) and Wire Electronic Discharge Machining (WEDM) are non-conventional machining processes typically applied where difficult to machine engineering materials such as ceramics, composites and titanium alloys are required. These materials possess characteristics that make them suitable for specific applications at the expense of their machinability. The machinability of engineering materials can be quantified by a number of factors including required surface finish and micro-structural properties, material removal quantity and rate and power consumption. In conventional machining, the energy consumed is directly proportional to the cutting force of the machine tool. Thus, materials with lower machinability will have higher energy requirements during the cutting process. Suitable for producing near-net shaped components, AJWM and WEDM can also produce components that are acceptable without the need for further processing thereby reducing the total production energy requirements [57].

The energy consumption for AWJM is influenced by its process variables such as the efficiency of the motor, which drives the pump that supplies the required discharge pressure for cutting. Current AWJM R&D activities are concerned with these variables including water pressure, abrasive rate and grit, tilt angle and nozzle/orifice combinations. These affect the energy consumption levels required during the cutting process. Energy conservation approaches have also been investigated to correlate the AWJM input energy (ignoring energy losses) to the material removed. This has shown that more energy removes more material but resulting models require cutting tests to determine the process parameters and afterwards they are only applicable to the materials tested. These investigations facilitate the development of cutting head designs which have the potential to improve the overall energy efficiency of the process [57].

WEDM is one of the most extensively used non-conventional machining technologies and can be traced back as far as 1770 when the erosive effects of electrical discharges were discovered. With this technology, electrical energy is converted to thermal energy via an electrode during the sparking process (breakdown, discharge and erosion), which melts the material. Current WEDM research is focussed on the machining performance measures, process parameters and the design and manufacture of electrodes aimed at improving the material removal rate and surface finish [58]. A model approach has also been taken to describe the electro-thermal erosion that occurs during the process [59]. These investigations have revealed that while the discharge duration and travel speed affect the surface roughness, the discharge current has a greater impact on the material removal rate and conversely, the energy consumed [58][60]. Although higher melting energies can be used, this overheats the melting pool whereas using a minimal amount of energy to warm up and melt the material is a more efficient use of the discharge energy. The energy distribution throughout the process is important for determining the minimal amount of energy required and the absolute amount of material to be removed. This influences the efficiency of the process as material removal rates decrease with increasing gap width [60][61].



(a) Distribution of discharge energy (b) Energy distribution in workpiece

Figure 39: Energy Distribution

The recast layer (the amount of molten material that re-solidifies after discharge) is unknown but there could be a correlation between the input energy and the recast layer that could affect energy consumption during the process. Combining the high frequency vibration of the electrode during the process increases the discharge energy utilisation ratio and improves the cutting rate and surface energy. The working medium used is also important as it improves the material removal rates thus increasing the overall efficiency of the process [60].

The use of NC controllers helps optimising machining processes by eliminating causes of errors or compensating the results and adapting the machining parameters automatically to achieve the desired outputs. There are STEP-NC standards for machining processes including ISO 14649 part 13 [58][61], makes provisions for the WEDM process. The use of NC controllers certainly has the potential to improve the energy efficiency of AWJM and WEDM by providing real time monitoring information and adaptive control of process parameters [62].

There are other factors affecting energy consumption of AWJM and WEDM as well as the by-products of these processes, such as abrasive recycling or the use of green abrasives for AJWM, and environmental impact of the dielectrics used for WEDM. These are important particularly if their lower energy requirements come at a cost to the environment. These considerations will be investigated when comparing the energy consumption, efficiency and eco-friendliness of AJWM and WEDM with the conventional machining processes selected.

2.4 HANDLING EQUIPMENT

Adopting robotic technology probably is not the first thing to spring to mind when developing an energy-saving strategy for the factory floor, despite the fact that modern robots with servo motors are already very efficient relative to power usage. However, handling in modern day factories is mostly done with robots equipped with the appropriate grippers [63]. Applications of modern robots may include:

- Handling of cast
- Manipulation of heat treatments
- Manipulation of plastic molding
- Handling in the forging and stamping
- Welding (Arc, Spot, Gas, Laser)
- Use of materials (Painting, Adhesives & drying)
- Mechanization (Loading and unloading of machines, Mechanical cutting, grinding, deburring and polishing)
- Other processes (Laser & Water jet)
- Mounting (Mechanical assembly, Insertion, Adhesive bonding, Welded joint, Mount Handling)
- Palletizing
- Measurement, inspection, quality control
- Material Handling
- Training education and investigation

Robotic Grippers

Often called end of arm tooling (EOT) or end-effectors, robotic grippers are the physical interface by which the robot performs an operation. Grippers are used to take an object, normally the work piece, and hold it during the work cycle. Various holding methods can be used, in addition to obvious mechanical methods for clamp the pieces between two fingers. These supplementary methods include the use of fastening caps, magnets, hooks and forks. End effectors are a significant element of a handling robot and the energy they consume cannot be neglected. Flexible grippers come in four categories: pneumatic, vacuum, hydraulic and electric. A final category, hard tool or hard fixtures, are typically designed with locator pins for large operations and designed for a specific operation or part.

- *Vacuum Grippers:* This type of gripper has been the standard EOT in manufacturing, allowing greater flexibility of all the robot gripper types. Vacuum systems can generate a vacuum from compressed air, either through a venturi generator at the point of application, or from a remote vacuum pump. Vacuum pumps have been standard fare for decades in manufacturing environments. By funneling a vacuum through a rubber or polyurethane suction cup, these systems offer the greater flexibility of any other gripper type while delivering up to 300 kg/m^2 of handling capacity.
- *Pneumatic Grippers:* This is the most popular type of gripper due to its compact size, small weight and high clamping force. They can easily be incorporated into tight work cells, which can come in handy in manufacturing. Pneumatic grippers can be either opened or closed, earning them the nickname "bang bang" actuators because of the "bang" sound created by the metal-on-metal punctuation when operated. Pneumatic grippers operate faster than hydraulic grippers but with lower gripping force (~120 psi). The energy source is the compressed air between 5 and 10 bars. There are two

types of pneumatic actuators (Pneumatic cylinders), with the latter being generally heavier and with smaller efficiency, hence rarely used:

In pneumatic cylinders, actuation is achieved by moving a piston enclosed in a cylinder, as a result of the pressure difference on its both sides. Pneumatic cylinders can be single or double effect. In single effect, the piston is moved in one direction as a result of thrust by compressed air to the one side, while it is moved back by a spring. In double effect cylinders, compressed air drives the piston in both directions, because it can be introduced in any of two chambers. Normally, in pneumatic cylinders it is possible to position the clamp into specific end positions only and not continuous positioning. The latter can be achieved with a distribution valve to drive compressed air to one of the two sides of the piston alternately. Nevertheless, continuous positioning systems with pneumatic actuating due to their cost and quality are not very competitive yet. However, their simplicity and robustness are significant advantages in cases where positioning in two predefined positions is enough. The use of robots with some type of pneumatic actuating must have a compressed air installation, including: compressor, distribution system, filters, dryers, etc. However, pneumatic installations are frequent in a lot of factories which have a degree of automation.

- *Hydraulic Grippers:* These grippers provide the highest clamping force and are often used for applications that require a significant amount of force They work off hydraulic pumps and can provide clamping pressure up to 2000 psi and more. Although they are strong, these systems take longer to operate because the fluid must be evacuated between the gripper and pump, hydraulic seals can leak bringing more mess with oil used in the pumps and may damage the terminal actuator with their great force.
- *Servo-Electric Grippers:* These types of grippers are appearing more and more frequently in industrial settings due to the fact that they are easy to control. Electric motors control the movement of the gripper jaws through an electronic control. Electric grippers can be programmed to grip a part off center compared to the gripper's centerline. They can also vary the speed and rate of acceleration of the gripper, and provide force feedback of the pressure applied to the part through the gripper by monitoring the current applied to the servo, allowing flexibility in gripping force and detect if an object has been picked up by the robot. Moreover, a servo controlled end effector uses energy while it is operates. When the servo stops operating, the end effector can hold the product but not expend any energy. Servo-Electric grippers are also the cleanest and most cost effective choice, with no air lines. Simplicity and precision on control of electric actuators have played a significant role on their increased popularity.

  There are three types of electric actuators:

  - *DC motors – Servomotors:* They are the most commonly used due to their superior control characteristics. Rotational velocities in these motors vary between 1000 and 3000 rpm with a lineal conduct and low time constants. Their power can reach up to 10kW. DC motors are speed controlled in closed loop (servomotors). DC motors have the disadvantage of required maintenance of the brushes.
  - *Stepper motors:* Stepper motors are generally not used in the industrial sector, due to their small torque output and the existence of large steps between consecutive positions. In the last years they have improved so much, especially about control, that has been possible to make stepper motors able to develop sufficient torque in small steps. Their main advantage in comparison with

servomotors is their capability to ensure a simple and exact positioning. In addition they can rotate in continuous mode, with variable velocity, like synchronous engines, to be synchronized with each other, to obey to complex sequences of operation, etc. They are light motors, reliable and easier to control; the control is realized in open loop, without need for feedback sensors because each state of excitation of the stator is stable. Some of their disadvantages are that the operation in low velocities is not smooth, and there is always the possibility to do a position mistake when operating in open loop. Nominal power is low and their precision reaches typically up to 1.8º. They are used for the axes positioning that don’t need lot of power or for small robots; they are also very useful in peripheral devices of the robot, like coordinate tables.

- *AC motors:* This kind of motors hasn’t had application in robotics until some years ago, due to the difficulty of their position control. However, the improvements introduced in the synchronous machines are turning them to a good competitor for DC motors. There are two types of AC motors i) synchronous motors and ii) asynchronous motors with the latter to be still hard to control in respect to their position, so they are not used in robot applications.

An important consideration when designing for efficiency should be the weight and size of the EOT itself. Having a small, light weight EOT impacts the size and the complexity of the robot. Smaller and lighter robots save energy through down-sizing. The force that a robotic gripper applies to a part is typically used by engineers to select grippers. While gripper force is a first order consideration, the torque that is experienced by the gripper is equally as critical and, unfortunately, usually only addressed in a cursory manner.

Energy Efficiency increase of robots

Industrial robot’s power consumption can be characterized as very dynamic - a power of a regular 6 axes 200kg heavy payload industrial robot has a range from 0.5kW in stand-by mode up to 20kW at peak. It is highly dependent from particular robot type, application, tool, work piece, movement trajectory, usage strategy and many other factors, altogether building a complex set of influence variables.

Because of the largest market share, among all, the 150kg-250kg payload range heavy load 6-axes industrial robots today are the most low-priced ones, which is a reason why they are often chosen also for applications that do require far lighter load. Recent measurements have shown a difference in energy consumption of two robots carrying a 16kg load, can be up to 2.2 times bigger for the large robot.

Shutting down robots during their production-free time can save significant amounts of energy. A case study at the Mercedes-Benz plant in Sindelfingen showed a 275W saving per robot, or a total of 1.17MWh/year.

Due to the dynamic nature of the movements of a robot, with quick starts, stops and rapid direction changes, an opportunity for energy savings comes from recuperative motor braking. In that case, buffered energy in the capacitors of a DC-Bus generated when breaking a particular axis is used, thus, when one axis is braking, others can accelerate using that energy. However, often is a case, when several axes brake or accelerate in the same time, and due to the limited capacitance not all potential energy may be buffered. In this case, either more power from the network is provided or the energy is dissipated in balancing resistors of DC-Bus to reduce the overvoltage. [64] has estimated that possible efficiency increase can reach up to 6% if fully re-using the recuperated energy.

To catch up otherwise wasted energy, there are at least three ways:

- Share the DC-bus among several robots, creating a robot “Energy team”
- Increase the capacitance of dc-bus,
- Use of reversible rectifier

Sharing of DC-bus among the several robots is a promising alternative when coupling many robots. The DC bus of the energy team can also be supplied by a single, more powerful and efficient rectifier instead of several separate ones. The estimated energy savings is approximate to the amount dissipated in balancing resistors. The use of capacitor buffers for industrial robotics is another alternative, which can save a large part of braking energy. At maximum load and speed the amount of energy to be saved ranges from 6% to as much as 19%.

Further improvements can be made by optimizing the robots’ movement profile. By running the robot at lower speed, the total consumption decreases; running a robot at constant speed and decreasing the acceleration, the consumption decreases as well.

The cost-effective presumption would be, if decreasing robot’s speed or acceleration the energy consumption reduces faster than the cycle time increases, it is worth to implement such changes. Concluding, if there is a spare time to do the task slower, it is worth to do so.

Another way to achieve increased efficiency is point approximation; most robot controllers allow to fly-by the programmed process points within the predefined range and without stopping there. This effect creates a smoother movement, often shorter and therefore quicker.

Robots are usually equipped with mechanical normal-closed brakes. According to measurements, the average industrial robot’s motor brakes require 100-130W to keep them opened during the movement. When a robot reaches its target position is being kept in a still state by it motors’ stator currents. If there is no movement command after a certain amount of time, the motor drives are turned off and mechanical brakes are released –the robot is in a type of stand-by mode. According to measurements on KUKA series Quantec KRC4, the standby states are accordingly 510W, when drives are active, and 210W when they are off and brakes are released, which is a difference of 300W.

Also the power required opening the brakes and to keep them opened significantly differs. Universal timer-based power reducers are available on the market that after the power peak of switching-on decrease the voltage on PWM basis, which are often used for types of valves. According to measurements, to keep the brakes of motors open after they’re switched on, only 30% of the currently used energy is needed. This can deliver 60-80 W power savings. Combining all the described strategic usage approaches like appropriate robot choice, robot shutdown, stand-by mode active usage, trajectory optimization methods, the technical advancements like asynchronous brake management, brake power adjustment, more reusing the recuperated energy, the total energy savings can exceed 40% [65][66][67][68][69][70][71][72].

FANUC Robotics installed a robotic system replacing fixed automation that was hydraulically controlled [73]. An electric robot, when not moving, shuts itself off, so very little energy is being used, in contrary with the original equipment which had a standard hydraulic pump that pressurized fluid to perform work. When the system is not working, the fluid is dumped over a pressure relief valve which caused the fluid to heat. To cool that hydraulic fluid back, there is a chiller, which further consumes energy. Today’s AC servo-controlled robots use even less power than the DC servo-controlled robots of the past. Robot controllers can help lower the energy bottom line by turning off peripherals when they are not needed. Controllers can shut off motors, machine tool coolant pumps, and spindles. According to [63], [74] and [75], a lot of energy is expended on lighting, heating and air conditioning needed to provide a suitable environment for factory floor staff. With no requirements for minimum lighting or heating levels, robots offer great opportunities to directly reduce energy consumption without compromising quality of production. Current estimates point to a potential saving of 8 per cent for every degree C reduction in heating levels, while savings of up to 20 per cent can be achieved by turning off unnecessary lighting. A further increase in efficiency can be achieved by installing multipurpose robots, with the ability to perform multiple functions on the production line and complete a job in as little as half the time.

Robot cells are also being used to reduce waste. International Auto Components installed an automated cell at its factory in Sweden and says it reduced its defective parts rate from 150 parts per million to 50 parts per million. In a similar case, First Engineering in Singapore employed a six-axis ABB robot to produce ultra-precision moulds and plastic parts for use in high-tech products. This increased its output by 75%, up from 170,000 to 300,000 parts per month.

Robots can also help lower building costs by providing for smaller work cells. Floor space is a measure of energy usage because that floor space has to be heated, cooled and lighted. The more that can be produced in a small space, the less the building will consume in terms of energy. Lowering energy demands can be done through the use of compact robotics.

In the automobile industry more than 95% work in the body shop is done by robotics-related applications. Because of the high degree of automatization and cyclically reparative behavior of robots, even little improvements in the efficiency of their systems may result in significant energy and CO2 emission reduction in whole production.

3 INDUSTRIAL STATE OF THE ART

3.1 CONVENTIONAL MACHINING PROCESSES

3.1.1 Milling

Milling is traditionally used to shape, slot, pocket, bore, profile and drill products, but can have a multitude of other uses in the manufacturing industries. Most are fitted with an X,Y,Z axis orientation, with a table that moves along the X-axis which sits on a saddle that moves along the Y-axis. The spindle is housed on a milling head on the Z-axis.CNC milling is currently the most popular form of milling machine.

CNC machines are programmed by CAM software, which creates production cycles by creating codes. For example;

- G81 informs a drill to continuously spin unless told to stop, which would then be followed by parameters for drilling position
- S100 M03 tells a tool-head to spin forward at 100 RPM, or S5000 would tell it to spin at 5000 RPM. Replacing M03 with M04 would tell the piece to move in reverse
- M05 is the coding for a piece to stop

Tools are held in a spindle cartridge by clamping them in place before machining operations and releasing them afterwards via a pull stud. These tools are selected and automated by a control panel, which can either be manually administered or set in automatic mode to read programs. Modern milling machines are compatible with a number of different tool-heads. R80, NT40, CAT40 and BT40 are all supported. Face mills, end mills, chucks and drills are all compatible with the spindle.

Conventional milling is machining when feeding a work-piece against the cutter rotation. Climb milling is machining when feeding the work-piece in the same direction as cutter rotation.

There are some limitations to CNC milling as a manufacturing process such as size limitations in terms of parts that can be machined. This is crucial as the largest machine is around 100 by 25 feet and the smallest about 9 by 6 inches and components that are smaller or larger would require a different machining process.. Although CNC machines require little maintenance and can be operated continuously throughout the year, this can result in a lot of wasted energy as workers may not feel obliged to switch them off. They are also quite slow when compared to other machines. Another limitation is that milling machines are not capable of drilling square-edged holes in material so this part of the process would have to be done separately.

Newburgh currently uses around 30 individual milling machines throughout the business. Two examples of these (which are being observed in the business case) are the Unisign Univers 5 and the Mori Seiki MH63. These are both medium sized milling machines, which take up a substantial amount of floor space. These are both used in the machining of the Loading Ramp Hinge; drilling the holes, profiling the shape, milling the face and cutting the slots; a detailed process-chart for the machining of the hinge at Newburgh is available. It is programmed by a CAD-CAM system and then manned by one worker, and 30 items are produced a month. There are three separate fixture set-ups, and around 20 different tools are used. The whole process takes around 4 hours to complete and uses electricity, coolant, compressed air and carbide. Problems noted have been excess steam being produced by the heat and the coolant, requiring a de-mister to be attached to make working conditions bearable. Also, there has been some communication problems between a sensor in the spindle and tool-heads, where the spindle doesn’t recognize that some tools are there, meaning that the switch has to be made manually.

Eco-Friendliness

- *Swarf and general wastage:* Swarf is very easily controlled and recyclable. It is common for a conveyor belt system to be in operation within a milling machine. This transports the swarf to a skip or elsewhere to be recycled. The tool heads quite often use carbide tips, and these can also be easily recycled and turned into useful waste.
- *Hazardous gas:* A lot of the hazardous gas is removed by the de-misting device, but others are produced during the milling process.
- *Liquid waste:* The bulk of liquid waste is the used coolant that is required to aid cutting. Most machines have a system in place whereby coolant is drained from the machine, then re-used or recycled.

Energy Consumption, Cost and Efficiency

- *Electricity:* It is estimated that the average use of electricity by a medium-sized milling machine (while being used and on standby) is approximately for a year. This is obviously quite high, and it needs to be looked into how energy could be saved by cutting down the need for power. In a CNC milling machine the power is supplied by highly accurate servomotors.
- *Coolant:* An awful lot of coolant is pumped to lubricate and cool the cutting, throughout the entire process. It is suggested that using coolant at all may not be completely necessary. In the case of some metals (steel, brass) coolant is not required at all, and aluminium could use an alternative such as WD40. This really needs to be researched into.
- *Air Pumps:* Air is constantly pumped into the machine. Parts are also often washed down with air, and this could probably be done by hand or water.
- *De-mister:* Such a vast amount of mist can be accumulated by the heat and coolant of the machining process, that it can be necessary to attach a de-misting device to the machine. This obviously uses energy and costs money. It is arguable that it improves efficiency however.

What can be improved?

Based on market knowledge and Newburgh’s own experience with machines we are able to deduce that the following features could be implemented in order to improve the manufacturing process of milling machines:

- The machines need to be more closely regulated so they are not left on continuously. Although they are perfectly fine to run all year round, it wastes an extortionate amount of energy. A device that shut down the power of different axles while not in use would be useful.
- Alternatives to coolant could be implemented into the assembly of the machines, or a system that encourages re-using of the coolant, and prohibits waste as much as possible.
- Another improvement that could be made to the machining process is that the machines could be made even more flexible, so as to machine an even wider selection of parts.

3.1.2 Punching

PRIMA-POWER is a major manufacturer of punching machines. Their current range consists of servo operated machines with one exception. Servo operated turret punch presses offer versatile punching, nibbling, forming and bending capacity on a single machine tool. Moreover, they also feature:

- Low connection power
- Low power consumption
- Low maintenance costs
- High speed
- High accuracy
- High repeatability

The first FINN-POWER turret punch press which was based on the servo electric technology was brought to market in 1998. The punching and forming stroke are based to a horizontal movement, which is carried out by the servo motor. The horizontal movement is converted into mechanically vertical ram movement and is conveyed to the punching or forming tool. In the punching procedure the servo-operated wedge is moved over the roll which hits the ram and the ram and the tool goes down. When the ram has reached the programmed lower limit, it is returned back up pneumatically. In the forming procedure the ram movement is programmed to stop when the desired forming position is reached. After this, the returning movement of the roll and ram starts. The punch is numerically controlled, so the forming is very accurate. The static force required by the forming corresponds to the punch maximum force even when the ram is in its place. Naturally, there are no oil-related costs. In the electric servo construction there are substantially less critical components than in the traditional servo hydraulic machine. This means high availability and very low maintenance costs.

Questions about energy saving

- How much energy has the effect of the cost?
    - Significant costs derives from
        - The machine investment
        - Used material
        - Material utilization rate
        - Tools
        - Labour
        - Facility
- Higher energy consumption differences arise between the different technologies
    - Servo punching
    - Hydraulic punching
    - Laser cutting
    - Water jet cutting
    - Plasma cutting
    - Etc.
- Is there a less energy intensive machine manufacture economically viable?
    - Are customers willing to pay for it?
    - Is it enough just the green values?

What do customers expect from machine manufacturers?

- More automation
    - Less labour
    - More productivity
- More productivity

  - Automated programming tools
  - Production reporting
  - Machine Performance reporting
  - ERP connection
  - Production simulation
  - Optimization of production
- Machines of different sizes
  - Standalone without/with automation
  - Whole lines (Punch/shearing/buffering/bending)
  - Automatic storages for materials and parts
- The software that manages the entire system
  - MES (Manufacturing Execution Systems)
    - Programming
    - Order handling
    - Routing
    - Production Track & Trace
    - Reporting
    - Production performance analysis
    - Etc.
- Low connection power
  - It is possible to use the machine in remote areas where electricity supply is not at a high level
- Determination of the manufactured part rate automatically by using the appropriate parameters.

Open points/problems

- Energy consumption is measured relatively easy, but targeting the correct phase of work is challenging.
- What parameters should collect from the machine?
- It would be good to create an algorithm that can calculate a number of different variables on the basis of actual consumption.
  - Power consumption
  - Material utilization rate
  - Tool wear etc.
- Values of input parameters which cannot be measured should be determined, i.e. salaries, rents, etc.
- The machine maintenance necessary to set automatically on the basis of the measured values. For example, increasing friction, operating hours etc.
  - This ensures high machine utilization and productivity
  - Maintenance contracts proof of the importance of customers.
- How can the machine take advantage of waste heat for space/hall heating?
  - This is only a part of the year and to countries where the demand for heat is greater

- Applies shall be determined by the meter device, sub-processes, production lines, factories. So, only applies to measurements of pure punching machines or all the pieces work. For example, welding, painting, etc.
    - If the measurement is made separately, must be able to meta-CAM count cumulate and separately.
    - For creating measurement system it is necessary to invest a lot, so the instrument cluster is enough comprehensive information the potential for improving planning.

3.1.3 Forming (press)

The press is a machine tool that exercises continuous and progressive pressure on the material being worked. The press operates on the piece by inserting the suitable element, the mould, which, with its characteristics, performs a specific forming process; thus, the combination of the press and the mould makes it possible for a large number of workings to be performed (including variations and combinations of processes such as slicing, pressing, drawing, bending) with an enormous versatility of masses and dimensions of pieces, as with the level of precision and dimension (from millimeters of large press-forged pieces to precisions of the order of hundredths of a millimeters for fine slicing).

In addition, the processes carried out by presses may be further subdivided into two large families, depending on the temperature of the piece worked, which may be near to melting point while the material may remain in the solid state (e.g., hot-molding, with steel temperatures of around 900-1100°C) or an ambient temperature (that is, cold molding). Of the various possible classifications among presses, these differ according to the operating principle, depending on mechanical construction and the material being worked. In this investigation we consider only presses for the working of metals in the form of sheet metal or band and cold working.

Most relevant uses of presses on the industry:

- *Automotive:* Parts for bodywork, frames, finishing; engine components, transmissions, brakes and other groups, accessories and components.
- *Aerospace:* Components and structural parts.
- *Electrical machinery:* Parts for connectors, shearing of sheet-steel for the construction of electrical machinery, components for connectors, switches, etc.
- *Electric domestic appliances:* Bodywork and components in sheet-steel, sheared or drawn.
- *Power production:* Press-forging for semi-finished pieces for rotors, shafts, blades, etc.
- *General mechanics:* Molded, sheared, punched, minted, press-forged, with variable dimensions from a few millimeters to a few meters.

Outline of the Market

The world production of presses is dominated by Japan and Germany, followed by Korea, Italy, Taiwan and Spain. The ranking of the last years changed only slightly, but showing and ever increasing market share of the Asian countries already mentioned. It is worth mentioning briefly which are the main market characteristics and factors that press OEMs have or leverage in each of the above countries.

1) *Japan*

There several OEMs of small, medium and large size (up to 30,000 employees) and the local market is characterized by strong competition. Mostly OEMs play on more typical market leverages such as price reduction and the development both of new types of product (such as the servo-presses) and innovative mechanisms, which enable presses to work, even with difficult materials such as high-resistance steels. Presses with a striking force exceeding 1,000 ton, will find application almost exclusively in the automotive industry (especially those exceeding 3,000 ton). For the presses that have strength of pressure between 50 and 1,000 ton, their main market outlets are the automotive and household industries. Lastly, the small presses (less than 50 ton) are found in the household business and in the working of sheet-steel. A lot of Japanese manufacturers produce this type of press, even though, due to their relative simplicity, market requirements are mainly met by imports of Korean and Taiwanese origin.

2) *Germany*

The main market leverage of these manufacturers lies in their ability to offer a full support to their customers, from the initial stages of the process (machinery specifications in the language of the customer), passing on to the design and building stage (which means satisfying technical demands and allowing space for customers), until the post installation stage is reached (speedy and efficient customer service, 24 hours a day 7 days a week, and long credit terms up to 3-5 years). The main characteristic found among German manufacturers is reliability: they are able to boast three shifts per day, which means more than 6,000 hours per year, without ever stopping, except to replace a worn-out piece or for scheduled machine maintenance. In the case of German presses, rather than as regards their dimensions and tonnage, it is possible to distinguish the areas in which they are more often used as being based on the country of destination. Thus, in Germany and the United States, more than 70% of German presses are found in the automotive industry and related companies. In China, on the other hand, German presses are widely used in the house-ware area.

3) South Korea/Taiwan

In these countries OEMs are today able to provide a quality standard at a reduced production costs, but that, on the other hand, still has a technological gap compared with what Western countries have to offer. South Korean manufacturers have an output that expands from the small press to the large press and that, apart from meeting local market requirements, is exported to Japan and the United States, especially as regards low-tonnage machines. Taiwanese goods on offer are centered mainly on the molding of electronic components and hardware computer parts.

4) *Italy*

Italian OEMs manage to compete on factors such as high technology content and the ability to meet customer’s specific requirements. The strengths on which they concentrate their attention are the optimization of the manufacturing process and reduction of the time cycle.

Italian companies do not sell their products only to firms belonging to the classic users of presses, such as the automotive and household industries. Thanks to the high level of specialization they manage to find widely varying market niches, which may vary from tanks to lids and pots, from satellite dishes to fire-extinguishers, from trays to aluminum containers of high pressure gas, obtained by cold extrusion, from deep-drawing to shearing, until we get to the coining of high-speed stator packs with very high precision moulds.

5) *Spain*

The market leverage that larger Spanish manufacturers mainly go by is that of reliability, the guarantee of a long average lifetime (on an average, machines are normally replaced every 15 to 20 years) and, above all, the ability to count on brand loyalty. The market output for Spanish presses is the usual one: that is, components for cars and household goods. In particular, the Spaniards produce molding presses for the manufacture of bodywork parts, and shearing and molding lines for the production of small parts, as sheet-steel rotors and stators for electric motors.

Current status

- The introduction to the market of high-speed hydraulic presses, which are now able to guarantee speed and production capacity similar to that of the mechanical presses, are characterized by a lower production costs.
- In the large presses production the technological improvements introduced in recent years regard above all automation and the introduction of numerical control, while in the small presses production the main innovations concern above all the safety systems.
- The development of systems for the automatic supervision of maintenance and for diagnostic assistance has brought about both an improvement in the control of production (reduction in the number of pieces rejected by quality control), and a reduction in the time required to train the staff in the use of machines.
- The development of electronic systems able to perform the control of pressure, the precision control of the active and passive parallelism, to avoid breakages in the mould and to control the number of strokes.
- The tendency to electrify mechanical devices, with controls (servomotors) that act directly on the kinematic motions that lead to the movement of the working tools, will also bring about the replacement of the conventional machines with their mechanical controls. This trend is also evident in the presses, with solutions that make for greater control of the forces and speeds connected with the process of metal-forming. Servomotors of large dimensions have recently been introduced to the market increasing the use of presses to an extent never achieved before. These servomotors, together with numerical control, have enabled the presses, on the one hand to reach repeatability and precision greatly superior to what they could do in the past and, on the other hand, an increase in the lifetime of the moulds used. In particular, a reduction in wear and tear of the mechanical parts significantly limits the number of downtimes of the machines. Moreover, NC makes for coordination with other auxiliary systems, such as robots for loading and transfer, thus optimizing the productivity of the process.
- An increase in the use of Near Net Shape technology that, especially through the encouragement of the automobile industry, is acquiring an ever greater slice of the market. In particular, space is being found for the production of shafts with channeled profiles and other components with rotating dimensions that can now be obtained by means of presses. There are more and more companies that are active in this field, thanks among other things to new types of machine that are currently prototypes at some of the research institutes.
- With increased insistence on applications by users, especially in the automobile and aerospace industries, solutions are being developed for the machining of difficult materials (light & high-resistance alloys, sheet-metals in high-resistance steel, tailored blanks, etc.).
- Specific accent on reduction of energy consumption (servo-presses vs. hydraulic/mechanic, EU regulations, design solutions aimed at energy recovery).

An important aspect as regards the importance of manufacturing processes concerns the power output used in manufacture. The following chart indicates what we mean.

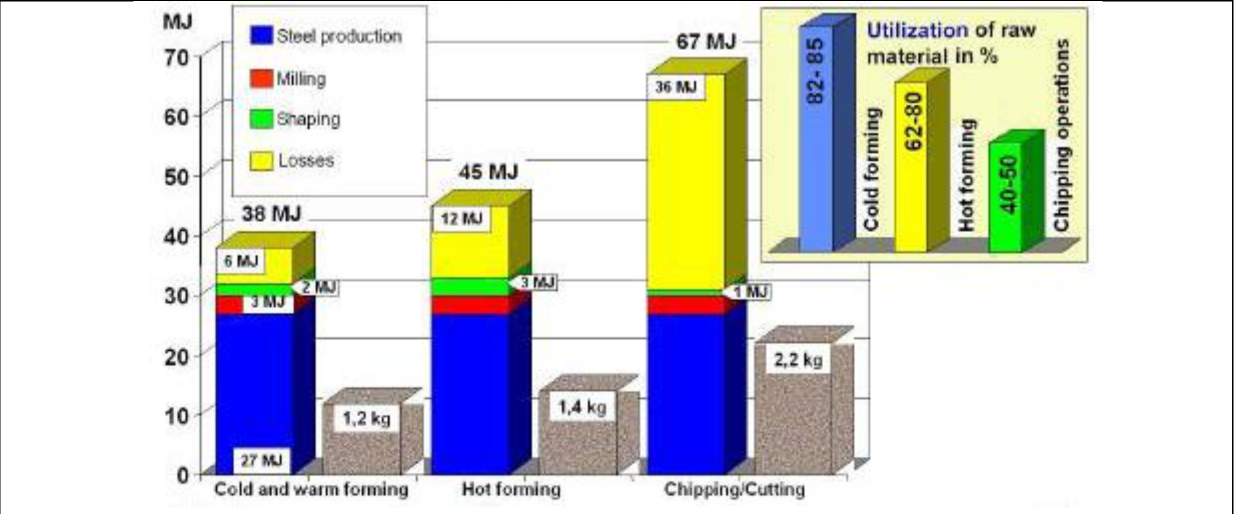


Figure 40: Total energy demand for 1kg "finished part"

From the chart above it can be seen that metal forming processes are more competitive than metal cutting, from the point of power consumption during the working cycle and from the point of material utilization [76].

Hot Forming processes as of today

Hydraulic presses show an important criticality when working on hot metal sheets. In fact in these conditions it is particularly difficult to control the piston movement acting on the pressure only, due to the metal sheet resistance that is not determined with the needed accuracy (non-homogeneous mechanical characteristics).

Hot Forming processes (for Aluminum/Steel Alloys) that influence the press design (new design with reduced tonnage, controlled blank-holder in different sections with mould designed with multiple effects). Specifically for Steel Hot forming processes (i.e. for high-resistance steel):

- Metal sheet forming by the press is performed using temperature, and insulated mould & press elements
- Heating system in industrial furnace
- Handling/transfer system on rollers using robots with grippers
- Mould designed with channels for cooling / quenching
- Localized heating system (induction type, laser, etc.) on the outer perimeter for bordering/cutting operation.

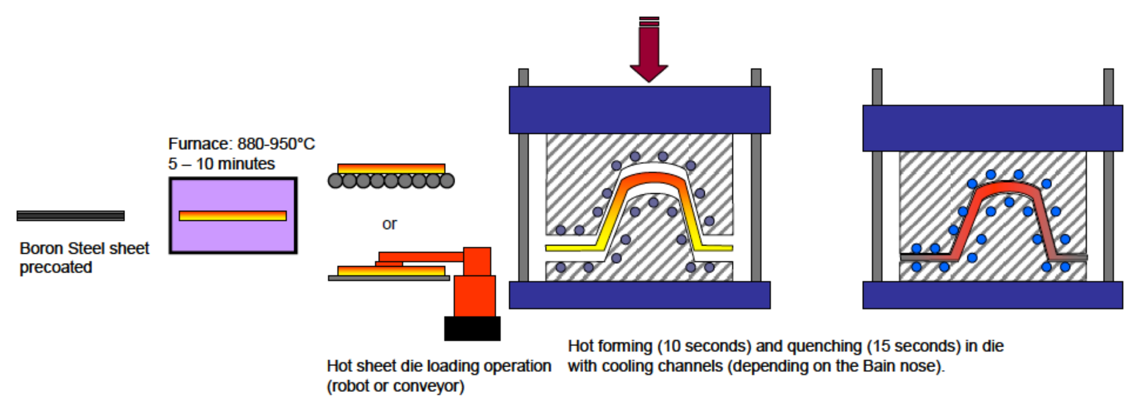


Figure 41: New hot forming process

New Hot Forming processes scheme:

- Metal sheet forming by the press is performed using temperature, and insulated mould & press elements;
- Heating system in industrial furnace;
- Heating keeping system in mould fitted with suitable resistances (to allow increased blanking operations)
- Gas forming system and mould for gas forming (high pressures are used)

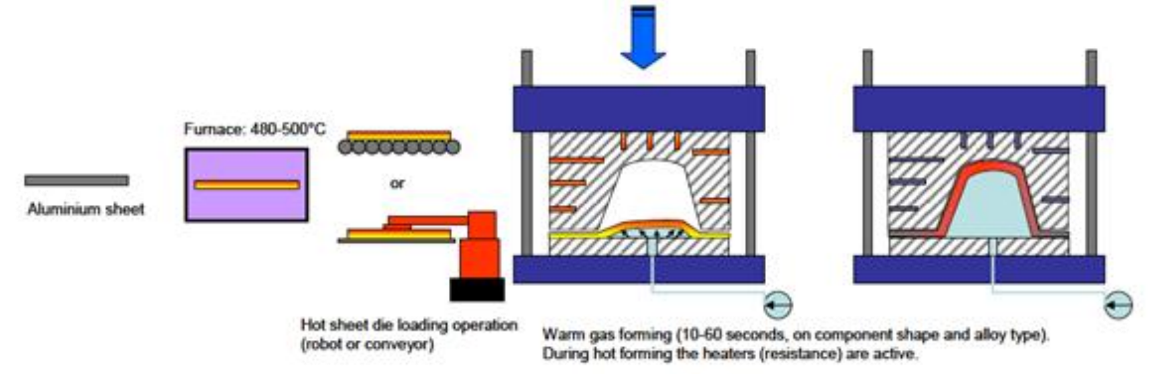


Figure 42: Example of light alloy hot forming process

Logistics aspects

More and more systems and process optimizations in production line crossing through timing, to improve production costs. This objective is pursued through:

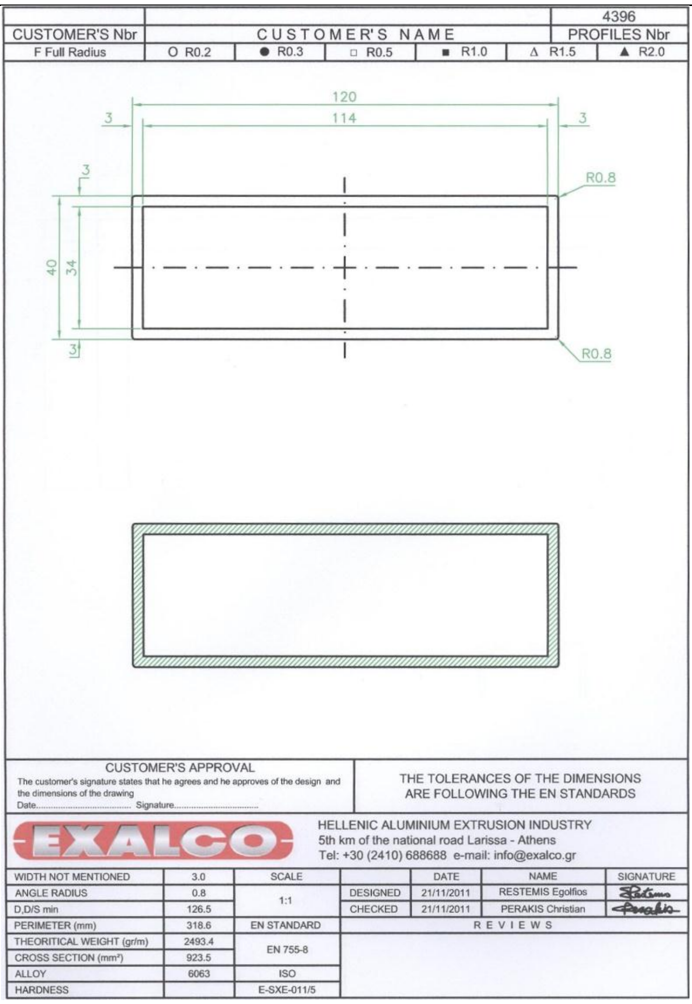
- Process & manufacturing simulation to identify areas of inefficiencies.
- Integration of all machines belonging to the same production line (material and data flow)
- Close attention to the complete manufacturing cycle, also through the supply of added high-value services (turn-key project design) and analysis of tasks before and after the forming process itself (welding, bordering, specific material alloys supply, etc)

3.2 NON-CONVENTIONAL MACHINING PROCESSES

3.2.1 Extrusion

EXALCO S.A. is an integrated industrial unit producing aluminium profiles and shaping sheet metals. The plant uses the extrusion for the production of geometrically complicated aluminium profiles. The plant is fitted with extrusion units containing four presses of 1,100 tones, 1,750 tonnes, 2,200 tonnes and 2,840 tonnes respectively, with production capacity of 33,000 tonnes annually, as well as a section producing extrusion dies. Their speed varies from 4m/sec up to 10m/sec, depending on the produced extrusion profile. Average energy and gas consumption of the extrusion units used for aluminium extrusion is 0.24kWh/kg and 0.027m^3/kg respectively.

Figure 43: EXALCO extrusion machine installation



						4396
CUSTOMER'S Nbr	CUSTOMER'S NAME					PROFILES Nbr
F Full Radius	O R0.2	● R0.3	□ R0.5	■ R1.0	Δ R1.5	▲ R2.0

CUSTOMER'S APPROVAL
The customer's signature states that he agrees and he approves of the design and the dimensions of the drawing
Date.......................... Signature..........................

THE TOLERANCES OF THE DIMENSIONS ARE FOLLOWING THE EN STANDARDS

HELLENIC ALUMINIUM EXTRUSION INDUSTRY
5th km of the national road Larissa - Athens
Tel: +30 (2410) 688688 e-mail: info@exalco.gr

WIDTH NOT MENTIONED	3.0	SCALE		DATE	NAME	SIGNATURE
ANGLE RADIUS	0.8	1:1	DESIGNED	21/11/2011	RESTEMIS Egolfios	
D,D/S min	126.5		CHECKED	21/11/2011	PERAKIS Christian	Perakis
PERIMETER (mm)	318.6	EN STANDARD	REVIEWS			
THEORITICAL WEIGHT (gr/m)	2493.4	EN 755-8				
CROSS SECTION (mm²)	923.5					
ALLOY	6063	ISO				
HARDNESS		E-SXE-011/5				

Figure 44: Typical aluminium extrusion profile produced by EXALCO

3.2.2 Laser machining

On the following table, a quick comparison between the main laser technologies is done. As one can see, fiber lasers easily outperform CO_2 lasers in terms of energy efficiency. In consequence of the significant advantages of the fiber laser source, together with considerable economic savings which will be the future in laser machinery, in the ENEPLAN project only this kind of source will be used and exploited.

	CO_2 laser	**Fiber Laser**
Laser system	Laser based on a gas mixture in which light is amplified by carbon dioxide molecules.	Diode Pumped Laser with a doped fiber as gain medium where most of the laser module is made of fiber
Reflectivity	Less effective for cutting highly reflective materials, since much of the beam is reflected back towards the source and not absorbed by the substrate. As a result, higher power levels are required for cutting.	Much less power required for cutting reflective materials like aluminium or copper since more of the laser energy is absorbed by the substrate. This allows for intricate high quality cutting at higher efficiencies.

Reliability (MTBF)	Only around 20,000 hours	50,000 to 100,000 hours
Power Consumption	High Power Consumption	Very Low Power Consumption
Maintenance	Heavy	Minimum
Power Efficiency	Only as high as 6-7%	Greater than 30%
Optical Path/Beam Path	Mirrors and optical path. Loss of beam quality and significant power drop.	Flexible Cable (up to 50m)

Table 5: Comparison of two main types of laser

Fiber lasers have been very quickly adopted by the industrial sector, given its clear and significant advantages, including higher energetic efficiency, as demonstrated by the declaration of some key laser machine manufacturers, herein reported.

“The fiber laser provides a dramatic improvement in energy efficiency when compared to the more traditional CO_2 resonator, leading to as much as a 50% reduction in the hourly operating cost. Coupled with that savings is the elimination of routine resonator maintenance and optical beam alignments” [BLM Group]. Moreover the electrical efficiency of Yb laser is greater than 28 % (wall plug efficiency) vs. 1.5% to 2% for lamp pumped YAG.

CY Laser 4KW	CO2 4KW Laser
33% Wall Plug Efficiency	8% Wall Plug Efficiency
$4/hour Run Cost	$18/hour Run Cost
No Scheduled Maintenance	High Maintenance Leads to Down Time
Zero Start-Up Time	Up to 30 Minute Start-Up Time

Table 6: Comparison of CY Fiber Laser to CO2 Laser [77]

Type	Wall Plug Efficiency
Fiber Laser Ytterbium (Yb)	28%+
Lamp-pumped YAG	1.5% - 2%
Diode-pumped YAG	10% - 20%
Disc	15% - 25%
CO2	5% - 15%

Table 7: Comparison of CY Fiber Laser to CO2 Laser [78]

Other advantages of fibre lasers:

1) *Cooling:* The efficiency of the fiber laser also contributes to lower cooling requirements, which contributes to lower electrical usage. Lower power fiber lasers require only air cooling. Higher power fiber laser require water cooling that is generally simpler and less costly than for equivalent alternative laser technologies. Cooling also depends upon the particular production environment.
2) *Consumables/Replacement Parts:* Because of the highly efficient design of fiber lasers (better thermal management) and the use of telecom-grade single emitter pump diodes, less replacement parts (such as lamps and diode bars), labor and production down time are required. Many lamps and diode bars used in YAGs have estimated lifetimes of 2,000 hours and 20,000 hours, respectively. These are a fraction of the MTBF of single emitter diodes (> 100,000 hours) which mean that for the life of the fiber laser, is not necessary to replace the diodes. In all solid-state fiber-to-fiber lasers there are no optics to adjust or maintain, such as resonators mirrors, crystals, fluids and filters, as in conventional lasers.
3) *Maintenance:* Fiber lasers require no or low maintenance, depending on the output powers and other factors, as compared to conventional lasers. There are no optics to align and no warm up-times, as well as consumables/replacement parts. As a result, a substantial saving in maintenance is possible

4) *Capital costs:* With fiber lasers, the same laser can cut, weld and drill, lowering the investment costs as compared to purchasing and maintaining different lasers and laser systems for each of these functions.

Energy consumption and running costs are traditionally high on CO_2 lasers, however, the fibre laser source on the L1Xe cuts hourly running costs significantly as a result of factors that include: up to 70% reduction in energy consumption thanks to high source efficiency; cost per part reduced by more than 50%; lower impact on consumables due to the absence of optical path, mirrors and bellows; reduced maintenance costs; the elimination of laser gas; and the eradication of standby currents and source warm-up times [79].

With its unique and revolutionary architecture and its 6g acceleration, SYNCRONO of Prima Power is able to match the dynamics necessary to fiber laser technology on thin sheets. Also the energy efficiency of the SYNCRONO (small masses execute faster movements), is further enhanced with fiber laser. This technology allows a drastic reduction of the electric consumptions, thanks to the use of lower powers and to the high efficiency of the source, thanks to the simplicity of the laser, without turbine and filters and with reduced optical chain [80].

To sum up, the key advantages of fibre lasers over other laser technologies are its high beam quality, energy & power stability, giving higher power density and a greater breadth of control, as well as its low total cost of ownership. The high beam quality of the fibre laser enables the beam to be focused to a small spot with a correspondingly high energy density [81].

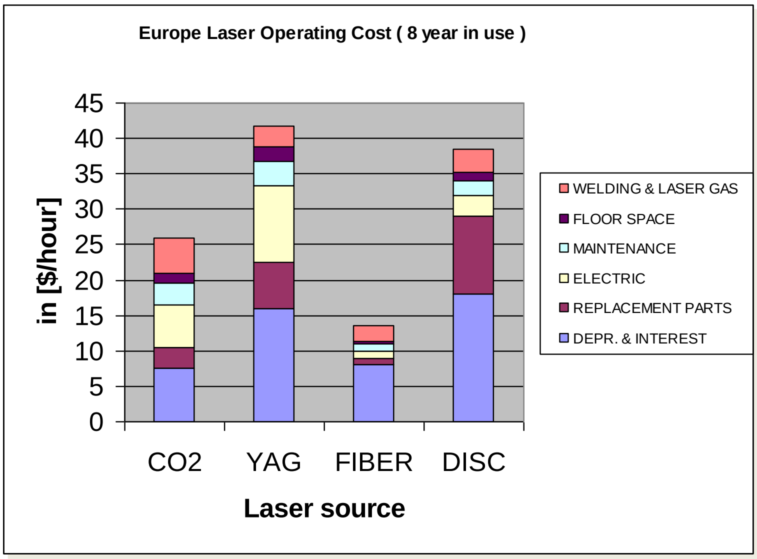


Figure 45: Europe laser operating cost

Fiber laser processing in different industries and markets

Laser cutting and welding are the most common processes in industrial applications, widely used:

- *In metal fabrication:* Laser processing has become the preferred method of manufacturing within almost all metal fabrication industries. Older processes that are now being replaced by fiber laser processing include stamping, shearing, punching and mechanical saws.
- *In the household industry:* The household industry has adopted laser processing significantly over the years. Some of the out-dated processes that have been replaced

by lasers; for this reason many companies have chosen laser processing as a necessary tool over the older conventional ways.

- *In the aerospace industry:* Laser processing is widely used throughout the aerospace industry. UID compliance has played its part in pushing laser marking, yet the versatility of laser marking has enabled laser processing to meet the strict guidelines which the aerospace industry must comply with.
- *In the automotive industry:* Laser processing is widely used throughout the automotive industry. Laser has been deemed the preferred method in direct part marking in lot of automotive application.

The above-mentioned industrial applications are only the main, but many other are possible in lot of diversified sectors, ranging from tooling to medical industry, from job-shops to semiconductor industry.

Trends and future developments

Yesterdays', today's and tomorrow's challenging and dynamic economic environment forces European high-end manufacturing industry to focus on high flexibility, high quality, reliability and low life-cycle costs and to respond quickly to changes in this environment. Despite that laser cutting and welding in recent years have reached a certain level of maturity, SMEs that use them are basing the selection of process parameters on data that usually derive from time consumption and costly trial and error approaches. These approaches are rarely lead to optimized conditions. Only the newest laser systems integrate, up to a point, process parameter data that typically derive from the laser system manufacturer. Moreover they are unable to make a comparison among different processes in order to assess what would be the best, considering different points of view, in terms of energy efficiency, cycle time, consumption, material waste and costs. Since laser cutting and laser welding are the two most popular processes in laser processing SMEs, the development of common/combined solutions for efficient manufacturing applications would be of significant benefit for laser processing SMEs and would be a clear competitive improvement. In particular the future of the laser will be due to the improvement of:

- the comparison with other processes
- the monitoring of several parameters such as:
    - power consumption
    - material utilization rate

in order to ensure:

- costs reduction
- low maintenance
- safety systems
- production control
- quality increase
- productivity increase
- flexible production, able to adapt to market fluctuation
- high energy efficiency

Focusing on energy use, apart from the energy consumption directly related to the laser source, developments proposed by machines manufactures [and Prima Power in particular] will generate, both as main objectives and as desirable side effects, further reduction in energy consumption, via various improvement strategies, as:

- machines with higher dynamics and accuracy that allow a cycle time reduction while preserving the required machining accuracy
- axes equipped by linear motors and a rigid structure, reaching a combined speed up to 240 m/min
- machine architectures with redundant axes to involve small inertias in small motions with high acceleration
- laser head with a highly dynamic focus axis to preserve an optimal beam focusing during fast motion
- For large production batches, more complete and faster automation solutions are recently offered (e.g. adjusting the pallet transfer speed according to sheet weight), increasing productivity and, consequently, specific energy consumption.
- Numerical Controls with a higher computational power and new advanced algorithms for predictive trajectory control and axes management, permitting a significant cycle time reduction

To reach optimal energy consumption in industrial applications is important to supply the user with information on energy consumption, both by monitoring during production and by prediction during cycle definition. Prima Power is developing, in its off-line programming system MAESTRO Libellula, an “Integrated Virtual Machine”, based on the actual machine controller, able to provide an accurate estimate of production costs and cycle times.

3.2.3 Wire Electro Discharge Machining

Wire EDM (WEDM) is one of the important non-conventional machining processes, widely used in aerospace, nuclear and automotive industries. WEDM has many well-known advantages, such as capability of accurately machining parts with complex shapes or sharp edges, high stability (through optimised flushing conditions) and high productivity. WEDM has been developed as an effective solution for a wide variety of materials including hard materials with intricate shapes. The process involves complex phenomena of generation of sparks and material erosion, which have been modelled by many researchers to solve the selection of optimum cutting conditions.

A Wire EDM system is comprised of four major components.

- *Computerized Numerical Control (CNC)*
- *Power Supply:* Provides energy to the spark
- *Mechanical Section:* Worktable, workstand, taper unit, and wire drive mechanism.
- *Dielectric System:* The water reservoir where filtration, condition of the water (resistivity/conductivity) and temperature of the water is provided and maintained.

Eco-friendliness

Most of the efforts in past decades have been to increase machining speed without reducing the machining accuracy, while considering various process-related constraints, like wire breakage. However, these approaches have not considered the impact of cutting conditions on the consumption of energy and wire, which are important for both economic as well as ecological points of view.

- *Wire Consumption:* Wire consumption is known to be one of the most important factors in WEDM machine tool utilization as it directly affects the waste generation and machine tool operation cost.
- *Dielectric:* WEDM uses de-ionized water as the dielectric. The dielectric system includes the water reservoir, filtration system, deionization system, and water chiller unit. During cutting, the dirty water is drained into the unfiltered side of the dielectric

reservoir where the water is then pumped and filtered through a paper filter, and returned to the clean side of the dielectric tank.

- *Filter System:* The filter systems are usually a quite simple installation, either paper-cartridge-filters or mineral filters. As there are no data available yet in terms of consumption for the recycling or burning of the filter, no definite conclusions can be drawn.
- *Hazardous Gas:* Among the main potential environmental hazards they cited the hazardous gas, vapour and aerosols resulting from the high temperatures developed in the dielectric fluid. Also, heavy metals may be carried by the dielectric and the sludge. Since a great number of hazardous substances are generated during the WEDM process it is very important to carefully treat and dispose this waste.

Energy consumption & efficiency

Recently, the energy consuming wire-EDM system components and the energy consumption distribution was determined for the GF AgieCharmilles Eco EDM FI 440 cc machine tool. It was found that a significant part of energy consumption was due to the water-cooling, spark generator and water injection systems. Subsequently different operation modes were studied by variations in the part height, wire diameter, part material, wire material and cutting rates. The obtained results show that by changing the cutting conditions higher energy efficiency may be obtained.

There are two types of components in the power distribution diagram:

- Process related power consumption components
    - Injection pump power consumption
    - Spark generation unit
- Process independent (constant) power consumption components
    - Filling Pump
    - Filter pump
    - Auxiliary pump
    - Cooler

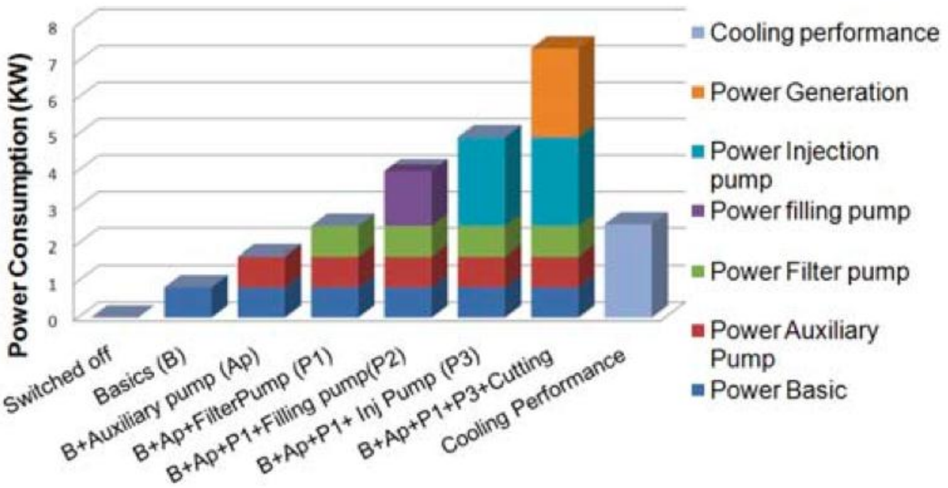


Figure 46: Power consumption of a WEDM system

The power consumption value of injection pump and spark generation unit depends upon the process (workpiece material, wire type and diameter, cutting quality requirement). In addition, the other categories of components (filling pump, filter pump, auxiliary pump & cooler) are not affected by the process requirements.

- *Filling pump:* Only in use when filling the dielectric into the work tank.
  - PFilling = 1.62 kW
- *Filtration pump:* Forces the dielectric through the filters from the polluted tank to the clean tank.
  - Filtration = 0.81 kW
- *Auxiliary pump:* Supplies the ancillary functions (threading jets, cleaning, wetting of wire contacts).
  - PAuxiliary = 0.81 kW
- *Injection pump:* generates the pressure for the high-pressure injection.
  - PInjection = 0 ... 2.43 kW (depends on injection pressure)

From the Figure 46, the difference between total power and power of pumps is equal to generator power. Generator power depends on used technology for the machining. Moreover, generator power and cutting speed are functions of discharge frequency. Therefore, PGenerator = 0 ... 2.37 kW

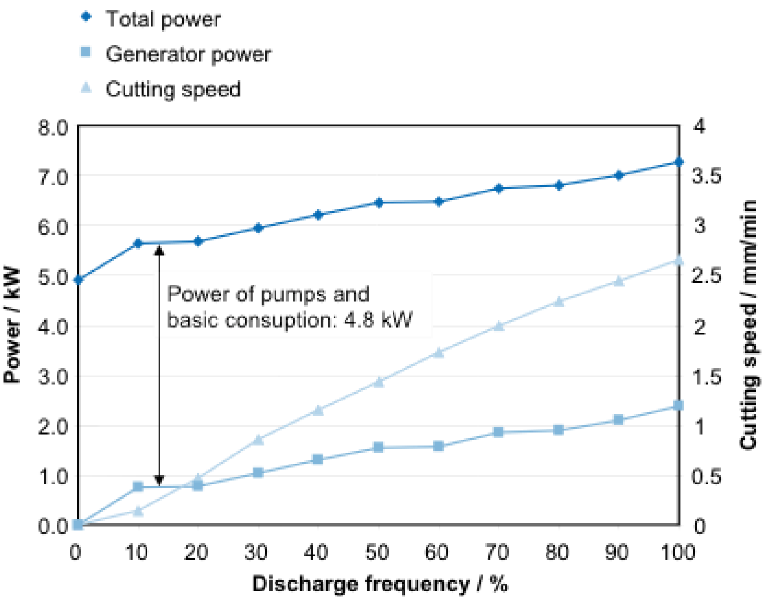


Figure 47: power consumption and cutting speed based on different discharge frequencies during WEDM processing

Cost

The costs of a WEDM machine have been calculated below. The initial capital investment was assumed at approximately €200,000. In addition, for the variable costs 3 labour costs have been identified: Full attention (100%), Split attention (50%) and Unattended (0%)

Fixed Costs	Value	Variable Costs	Value
Machine Cost (€)	150932.01	Wire (€)	1.72
Interest rate (%)	5.00	Labour (€)	40
Term (5yrs)	5.00	Labour 100%	30.19
Monthly payment (€)	2848.28	Labour 50%	15.09
Per annum	34179.31	Labour 0%	0
Insurance	16.60	Variable Hourly Cost (total)	
Repairs	1886.65	Labour 100%	31.9070259
Maintenance	3924.23	Labour 50%	16.81382538
Electricity	2608.11	Labour 0%	1.720624859
Space	792.39	Total Cost (fixed + variable) €/hr	
Total €	46,255.57	100%	€66.17
Productive hrs	1350	50%	€51.08
Fixed Cost €/hr	34.26338195	0%	€35.98

Table 8: Cost of a WEDM machine

Process and line flexibility

WEDM is an extremely flexible process. It is typically used to cut plates (as thick as 300mm) and to make punches, tools, and dies from hard metals that are difficult to machine with other methods. Along with tighter tolerances, multi axis EDM wire-cutting machining centres have added features such as multiheads for cutting two parts at the same time, controls for preventing wire breakage, automatic self-threading features in case of wire breakage, and programmable machining strategies to optimize the operation. WEDM is commonly used when low residual stresses are desired, because it does not require high cutting forces for removal of material.

Time efficiency

The fact that WEDM processing can be easily automated with palletized workpiece changing, and that no control of worn tools is necessary, make it an ideal technology to be run as an unmanned operation, with large cost benefits for the whole production cycle.

3.2.4 Abrasive Waterjet Machining

Although Abrasive Waterjet Machining (AWJM) is a relatively young cutting technology, created in 1979, its energetic and economic efficiency for rough cutting has been well proven as well as for the cutting of thin metallic sheet parts. AWJM has complete adaptability to cut almost any material and any geometry – there is no expensive tooling to be bought, so the process offers fast interchangeability and no set-up costs. Additionally, it can be used to rough machine parts, which can then be finished on higher-value equipment, reducing bottlenecks on these machines and improving productivity. As it is a cold process, there is no heat-affected zone (HAZ), reduced distortion and no work hardening, allowing second operations to be easily performed. AWJM has low running costs and is environmentally very friendly; “grey water” can be reused or fed directly to the drain, and dust particles are trapped in the fluid and deposited in the bed, reducing carcinogenic risk.

Current state of market

Today, the waterjet market touches most imaginable industries. With various grades of abrasive, abrasive jets around the world are cutting wood, aluminium, steel, titanium. It has found a place in many industries (aerospace, automotive) as well as most machine shops, and they are often used as an easy-to-use prototyping tool. Moreover, waterjetting technology is also used in many laser and Wire-EDM shops as a complimentary tool for high-speed rough cutting and preparation. The process no longer requires extensive operator experience. In the majority of the standard purchasable abrasive waterjets, the user simply inputs a design from a drawing program, a number representing the material, a thickness, and edge quality rating; the machine does the rest. Software has been optimized to minimize jetting effects such as taper, piercing and lag. Software updates frequently improve the performance of the machine as the cutting process becomes better understood, tolerances are tightened, and standards are heightened.

Eco-friendliness

In the current manufacturing environment, every manufacturing product and process is being evaluated in terms of its impact on the environment. For example, use of conventional coolants in machining and grinding is being looked upon critically from the point of view of its negative impact on environment. The environmental issues relevant to AWJM are listed below:

- *Water Use:* Firstly, any excess process water is simply drained to the sewer. In some cases, water treatment may be necessary prior to draining. However, in some instances, a "closed loop" system that recycles the water may be required – this may be the case when machining hazardous materials.
- *Abrasive Use:* In terms of abrasive recovery and reuse, provided that the material machined is not hazardous, the spent abrasive and waste material is suitable for landfill. Environmental issues and concerns have led the researchers to use such mediums and abrasives that do not require disposal, recycling or lead to pollution.
- *Energy Consumption:* The pumps do use a considerable amount of electricity; therefore, there is an additional environmental (and economic) impact. More information on the energy use of the machine, and in particular the pumps, is given in detail below, using a case study from Kurd (2004) on an OMAX 2652 Jet Machining Centre.

Energy consumption & efficiency

The abrasive waterjet and pump are quite simple from the energy standpoint. With the exception of the computer console, there are no components that are constantly running regardless of whether or not a part is being produced. A case study on was carried out on an OMAX 2652 machine and the results on the energy consumption are given below:

- *Computer Console:* The computer draws 110 V at 2 A while idle. This is constant for any amount of time that the machine is on. When cutting, the draw from the machine and motors increases to 2.2 A, implying that the motors require 0.2 A with 110V.
- *Motors:* Kurd [82] notes that there is no significant energy profile as a function of speed for the motors, and the existence of one would provide negligible values compared to the pump energy consumption.
- *Pump:* As regards the pump, the analysis shows that the direct drive pump contributes most of the overall power consumption during cutting. The pump receives 480V 3-phase power, is either on or off, and turns on 3 seconds before the cut begins. There is a spike in current as the pump ramps up; however, the current levels to a constant 25 A for the remainder of the cutting process. So for any given cut, the pump runs for 3 additional seconds before the cut begins. At the end of the cut, the machine stops the flow of abrasive while the pump and water run for an additional 1.5 seconds to clear the lines, before they are both shut down. For any cut the pump and water flow last for 4.5 seconds longer than the cut time.
- *Summary:* There is always a 2.0 A - 2.4 A current on 110 V, resulting in an average of 0.242 kW, and an additional 12 kW for the pump. Thus, we can see that the pump dominates energy use.

However, the average hourly power consumption for the pump system is roughly 16 kWh. This estimate takes into account the pump, servomotors, on/off valves, garnet distribution and water supply. This value is a more appropriate estimate with which to compare the theoretical energy profile for each cut, because it represents an average, not a maximum.

Cost

Initial capital investment can cost between €200,000 and €250,000.

In the table below compares the investment and operating costs, which are associated with a particular technology, such as the purchase, deployment and operation in single-shift mode. The comparison of various metal cutting technologies is made for the machining of a 10mm wide carbon structural steel plate.

Description of Item	Unit	Laser	Gas Cutting	AWJM
Investment acquisition of technology / equipment	€	415,000	135,000	235,000
Machine time @ 80% of use in 1 shift	h/yr	1,350	1350	1350
Value of annual depreciation	€/h	61.48	20	34.81
Loan payments (5%)	€/h	9.22	3	5.22
Insurance (0.25%)	€/h	0.77	0.25	0.44
Expenses on the area 80 m2 (leasing or payback)	€/h	3.56	3.56	3.56
Internal costs (maintenance)	€/h	9.22	3	5.22

Expenses on Energy consumption (1kWh:0.15€)	€/h	5.55	0.15	0.15
Work media	€/h	0.8	0	0
Expenses on tool	€/h	0.2	0.2	0.2
Handling expenses	€/h	0.5	0.5	0.5
Total	€/h	91.3	30.66	50.1

Table 9: Cost of a AWJM system

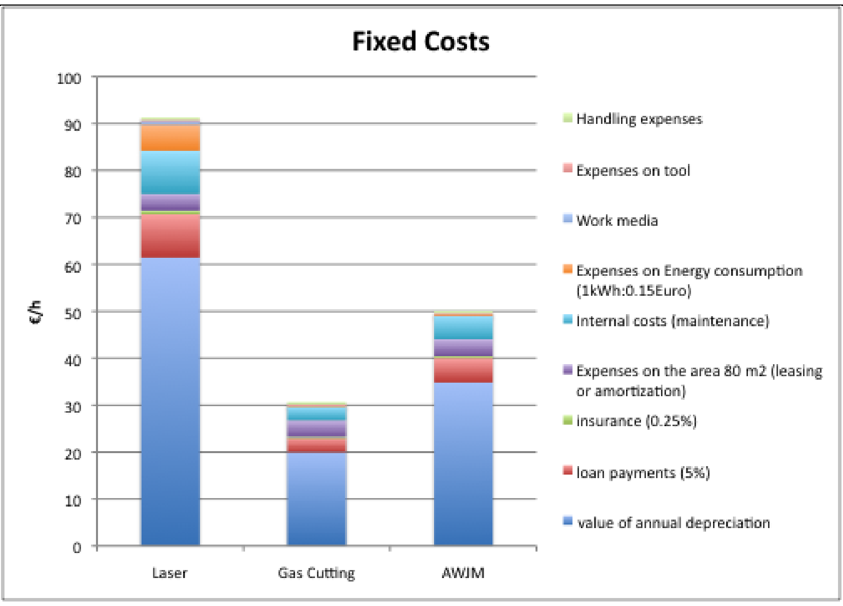


Figure 48: Fixed costs of an AWJM system

In addition, Prezel made the calculation of the total cost per meter of cut, which can be found in the table below:

Description of Item	Unit	Laser	Gas Cutting	AWJM
Speed	m/min	1	0.62	0.38
Fixed operating expenses	€/h	91.3	30.66	50.1
Total personnel costs	€/h	14	14	14
Consumption of technical gas	€/h	7.8	4.33	0
Consumption of abrasive	€/h	0	0	7.56
Cost of water	€/h	0	0	2.64
Cost of energy	€/h	1.95	0.15	2.64

Ancillary equipment	€/h	0.35	2.19	3.75
cost of consumption (4,5,6,7,8)	€/h	10.1	6.67	14.36
Total	€/h	115.4	51.33	80.69

Table 10: Total cost per meter of cut (AWJM system)

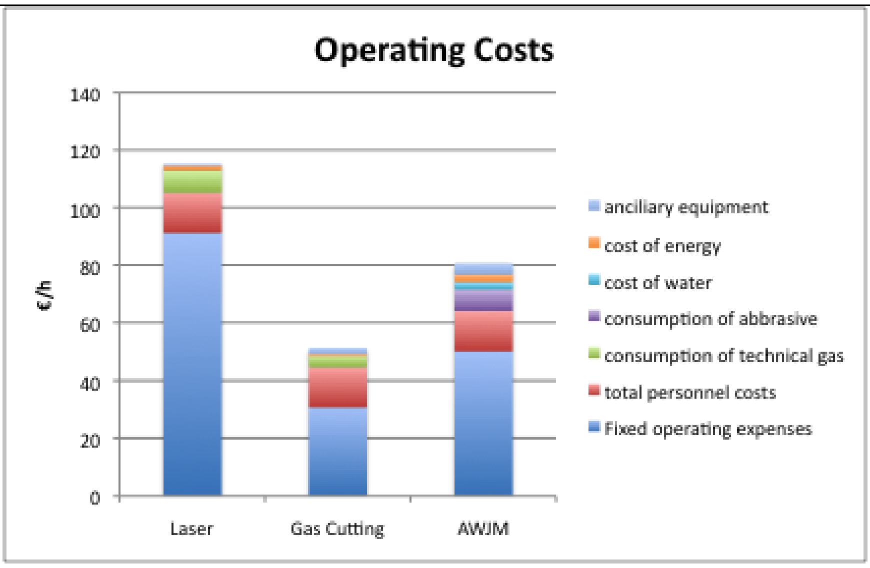


Figure 49: Operating cost of an AWJM system

Process and line flexibility

AWJ cutting systems are used for various materials and applications. Nearly all materials can be processed extremely well with waterjet cutting with abrasive. The limit is specified by the cutting tool. Garnet sand has hardness between 7.5 and 8.5 Mohs (this corresponds approximately to a Vickers hardness of 1200 HV to 2000 HV). Therefore, all materials that have a smaller hardness can be processed with waterjet cutting. The variety of the materials to be processed put waterjet cutting nearly in a class by itself. This flexibility together with the very short programming, setup, and processing times makes it one of the most economical production processes of all.

Time efficiency

- Fast setup and programming
    - With waterjet machining, a flat piece of material is placed on a table and a cutting head moves across the material (although in some custom systems, the material moves past a fixed head). This simplicity means that it's fast and easy to change materials and that no tool changes are required. All materials use the same cutting head, so there is no need to program tool changes or physically qualify multiple tools.
    - The movement of the machining head is controlled by a computer, which greatly simplifies control of the waterjet. In most cases, "programming" a part means using a CAD program to draw the part. When you "push print," the part is made by the waterjet machine. This approach also means that customers can create their own drawings and bring them to a waterjet machine for creation.
- Little fixturing for most parts

- There are very low sideway forces with waterjet machining; cutting the material doesn't push it. The downward forces are also small, in the range of a few pounds. Typically, the largest force is from the water in the tank pushing back up against the material.
- Fixturing is generally a matter of weighing down the material by placing weights on it. Small parts might require tabs to prevent them from falling into the tank.
- The low side forces, means you can machine a part with walls as thin as 0.01" (0.25 mm). This is one of the factors that make fixturing is so easy. Also, low side forces allow for close nesting of parts, and maximum material usage.

3.3 HANDLING EQUIPMENT

Grippers are active links between the handling equipment and the workpiece or in a more general sense between the grasping organ (normally the gripper fingers) and the object acquired. Their functions depend on specific applications and include:

- Temporary maintenance of a definite position and orientation of the workpiece relative to the gripper and the handling equipment.
- Retaining of static (weight), dynamic (motion, acceleration or deceleration) or process specific forces and moments.
- Determination and change of position and orientation of the object relative to the handling equipment by means of wrist axes.
- Specific technical operations performed with, or in conjunction with, the gripper.

Grippers are not only required for use with industrial robots: they are a universal component in automation. Grippers operate with:

- Industrial robots (handling and manipulation of objects).
- Hard automation (assembling, micro-assembling, machining, and packaging).
- NC machines (tool change) and special purpose machines.
- Hand-guided manipulators (remote prehension, medical, aerospace, nautical).
- Workpiece turret devices in manufacturing technology.

Definitions and Conceptual Basics

Grippers are subsystems of handling mechanisms which provide temporary contact with the object to be grasped. They ensure the position and orientation when carrying and mating the object to the handling equipment. Prehension is achieved by force producing and form matching elements. The term “gripper” is also used in cases where no actual grasping, but rather holding of the object as e.g. in vacuum suction where the retention force can act on a point, line or surface.

- pure enclosing without clamping
- partial form fit combined with clamping force
- pure force closure
- holding with vacuum air (pneumatic force closure)
- retention using magnetic field (force field)
- retention using adhesive media

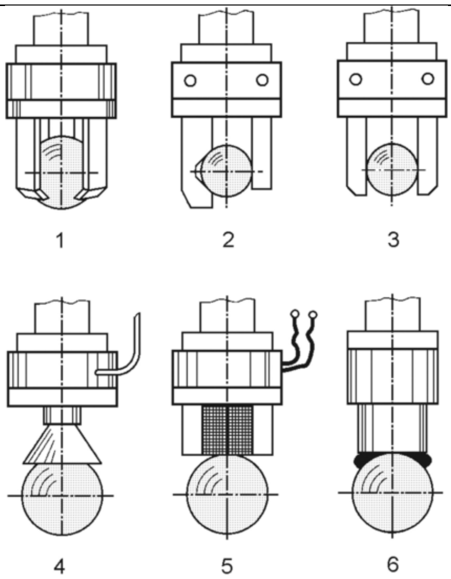


Figure 50: Possibilities for prehension of a spherical object

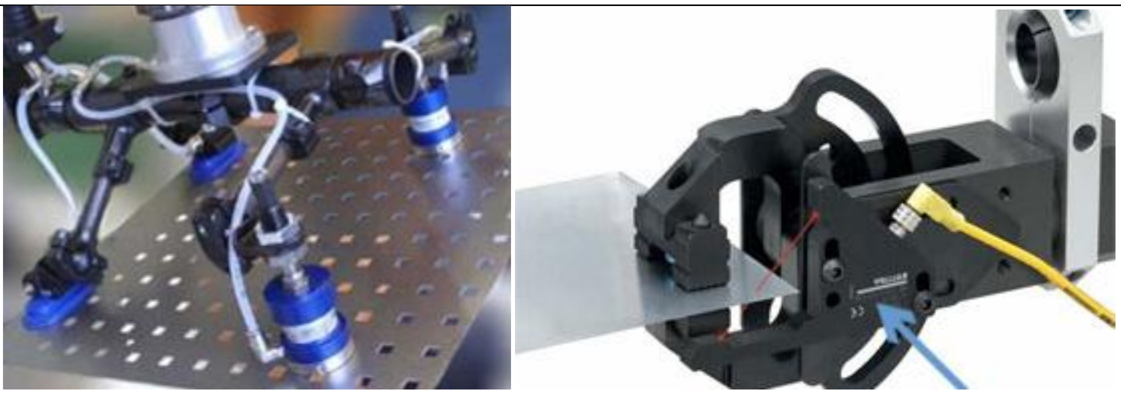


Figure 51: Suction grippers

Three of the most usual forms (impactive, astrictive and contigutive) of object prehension are depicted in six different examples in Figure 50.

One should differentiate between grasping (prehension) and holding (retention) forces. While the grasping force is applied at the initial point of prehension (during the grasping process), the holding force maintains the grip thereafter (until object release). In the many cases the retention force may be weaker than the prehension force. The grasping force is determined by the energy required for the mechanical motion leading to a static prehension force. The functional chain drive kinematics holding system is given, however, only for mechanical grippers. Astrictive vacuum suction grippers require no such kinematics (Figure 52).

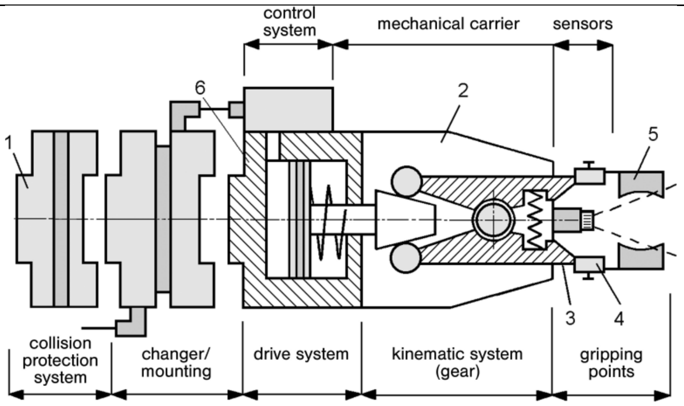


Figure 52: Subsystems of a mechanical gripper

There are some characteristic terms that are often used in prehension technology. Grippers consist mostly of several modules and components. In the following, the most essential terms used will be explained considering as an example a mechanical gripper. A short glossary of further important terms used in gripper technology is briefly explained below.

- *Astrictive gripper:* A binding force produced by a field is astrictive. This field may take the form of air movement (vacuum suction), magnetism or electrostatic charge displacement.
- *Basic jaw (universal jaw):* The part of an impactive gripper subjected to movement. An integral part of the gripper mechanics, the basic jaw is not usually replaceable. However, the basic jaws may be fitted with additional fingers in accordance with specific requirements.
- *Basic unit:* Basic module containing all gripper components which is equipped for connecting (flange, hole pattern) the gripper to the manipulator. The connecting capability implies a mechanical, power, and information interface. Figure 53 shows a flange design in accordance with DIN ISO 9409. This German industrial standard and its subsequent amendments contain design requirements concerning the different overall size, pitch circle diameter, centring cylinder dimensions, number of threaded holes and respective thread pitch as well as some position tolerances. The flange can also be drilled to allow feeding of power and control cables.

Figure 53: Flange design in accordance with DIN ISO 9409

- *Contigutive gripper:* Contigutive means touching. Grippers whose surface must make direct contact with the objects surface in order to produce prehension are termed contigutive. Examples include chemical and thermal adhesion.
- *Suction head:* A form of astrictive gripper which may consist of one or more vacuum suction elements (discs, caps or cups) from which air is actively evacuated by means of externally generated negative pressure.
- *Magnetoadhesion:* Prehension force by means of a magnetic field (permanent or electrically generated).

4 EXISTING PROCESS SIMULATION MODELS & MACHINE TOOL MODELS

4.1 BASICS CONVENTIONAL PROCESSES

Energy consumption of manufacturing systems has been extensively studied in past years. Most of the studies are focused on the energy consumption in machining. Many of those studies present methodologies that are generic ones and can be used in other manufacturing processes as well.

Dahmus et al [83] tracked energy flows in machining. The focus was to understand the energy consumption of metalworking and machining-based manufacturing systems. They characterized the environmental impact of machining, making a distinction between the energy required for chip formation and operating the equipment. The system can be studied at different levels of analysis: starting from that of the entire enterprise (the topmost level) and ending to the tool–chip interface (lowest level in the manufacturing hierarchy). Each of these levels of analysis has a corresponding temporal scale of decision making, which ranges from several days at the enterprise level to micro-seconds at the tool–chip level, (Table 11).

Level of analysis of manufacturing	Manufacturing analysis scale	Temporal decision scale
Supply chain management, Enterprise asset management	Manufacturing supply chain	Days-Hours
Production planning and scheduling	Manufacturing enterprise	Hours-Seconds
Macro-planning	Manufacturing equipment	Hours-Seconds-Milliseconds
Micro-planning	Sub-components	Seconds-Milliseconds
Process control	Tool-chip interface	Milliseconds

Table 11: Categorization of manufacturing analysis scales [84]

Supply chain management describes a process for planning, implementing and managing the flow of goods, services and related information from the point of origin to the point of consumption. Supply chain management and enterprise asset management includes subjects such as: manufacturing operations, purchasing, transportation, and physical distribution.

Production planning concerns the time-based allocation of orders to resources. Production planning and scheduling consist of several subjects such as demand and orders, ideal stock levels, materials and labor planning, machine routing and factory scheduling constraints.
Process planning is divided into two phases: micro- and macro-planning. In micro-planning, process, parameters, tooling and cutting fluids are selected for individual features, while in macro-planning interactions between features are examined. While micro-planning results in a process plan which is the aggregation of feature-level optimal plans, the aggregation of micro-plans does not necessarily result in a globally feasible plan. Macro-planning issues which have environmental impacts include process sequence selection for intersecting or nested features and feature clustering based on common setups and catalysts (e.g. tools and cutting fluids).

In micro-planning predictive process models can be used to obtain process level inventory of process energy, machining time, mass of waste streams (primary scrap and secondary catalysts) and quality parameters [85].

Process control is at the lowest level of the hierarchy and in e.g. machining operations it includes control of tool-chip interface. In the process control level the energy consumption can be remarkably affected. This can include functions such as selection of energy saving tools and monitoring the tool behavior.

4.2 LEVEL OF ANALYSIS OF MANUFACTURING SCALE

Srinivasan et al. [86] has used an approach for macro- and micro-planning of feature-based machining. Micro-planning looked at such factors as selecting process parameters, tooling, and cutting fluid based on process energy use, waste streams, process quality, and machining time. The study developed a thorough approach for process planning but the process energy usage was characterized only by the chip removal energy.

Igari et al. have implemented micro-planning systems that take into account the most relevant machining data by means of using an up to date machining data base. In the reference the idea is to update the database for an actual machine tool on the shop floor. The method is based on NC data analysis. Practical machining information of an actual machine tool is obtained from NC data by means of data analysis. The machining database is generated and updated by means of storing the obtained machining information for actual machine tools. The micro-process plan is generated for each actual machine tool on the basis of its own machining database. This system ensures that the most recent and relevant data is used for the plans. If energy of the machining operations is included in this data base, it may also serve as a tool for optimization of energy consumption.

In micro-planning, process, tooling and catalyst selection are made for a single feature. The simple aggregation of all the feature level micro-plans to form a complete process plan assumes unlimited resources for the facility. When efficient machine and plant utilization is aimed at, collecting of features with common process options to minimize setups, tool and cutting fluid types should be carried out. While the makespan of a component is driven primarily by the process conditions, grouping of features is important when determining the indirect production time (idle time). The macro-planning phase captures the interactions between features and generates an optimal machining sequence under precedence constraints such as tolerance stackup and, accessibility.

Toenissen [87] characterized the power consumption of precision machine tools during various types of manufacturing activity. The analysis is empirical.

Devoldere et al. [88] discussed the improvement potential in two types of manufacturing equipment (press brake and a 5-axis milling machine) of discrete part production. Power requirements for activities in a machine tool were classified into productive and non-productive periods. This type of analysis helps to design machines that have lower tare (or fixed: that is, energy consumed by the machine outside of chip formation) energy loads, and higher variable (or per-part) energy loads.

Dahmus and Gutowski [83] showed, for instance, that the specific cutting energy accounts for less than 15% of the total energy consumed by a modern automatic machine tool during machining. The rest of the energy is consumed for controller, fluid pump, fan and other ancillary devices. The spindle’s rotation and machines’ idle running consumes energy also at times when no cutting is done. The gap between the energy consumed by the machine tool and the actual energy used for material removal leads to possibilities to save energy. Figure 54 shows the energy breakdown from a modern, highly automated, mass production environment. It has been found out that also in smaller, less-automated machines a great deal of energy is used in non-cutting operations.

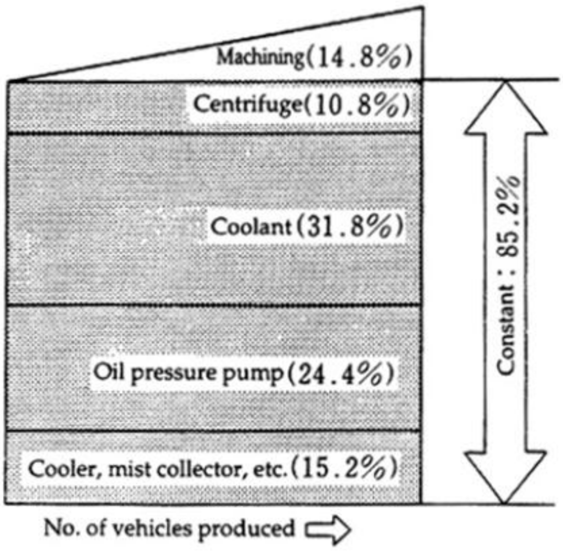


Figure 54: Machining energy use breakdown by type from Toyota [83]

He et al. analyses the correlation between numerical control (NC) codes and energy-consuming components of machine tools. He proposes a method for estimating the energy consumption of NC machining.

Mori et al. has made studies in order to reduce power consumption in machine tool operation by means of modifying cutting parameters and using a new acceleration control method (by synchronizing spindle acceleration with feed system).

A virtual machining models for analysing the sustainability impacts of machining process has been presented in [89]. Real world data such as machine specification data, life cycle analysis data, cutting speed, feed-rate, energy etc. was collected to determine the environmental impact factor. An extension work was conducted to incorporate LCA parameters into Discrete Event Simulation (DES) that was based on statistical characterization of shop floor process such as cycle time, idle time and failure rates.

Vijayaraghavan concludes in [90] the state of the art of the optimization of the energy consumption of manufacturing systems: past efforts in energy monitoring and analysis of manufacturing systems have been performed either as an accounting exercise, or by using theoretical estimates of the energy required for the various tasks and sub-tasks involved in manufacturing a part. The former approach is not granular enough to support decision making at the different levels, and the latter approach is not accurate enough, especially in complex systems. He proposes software-based approach for automated energy reasoning, which can support decision making across the multiple temporal levels in Manufacturing Analysis Scale, Figure 55. They have built the system on using MTConnectSM standard for data exchange. With MTConnectSM, the operational data of the machine tool can be monitored in context with the energy consumption data.

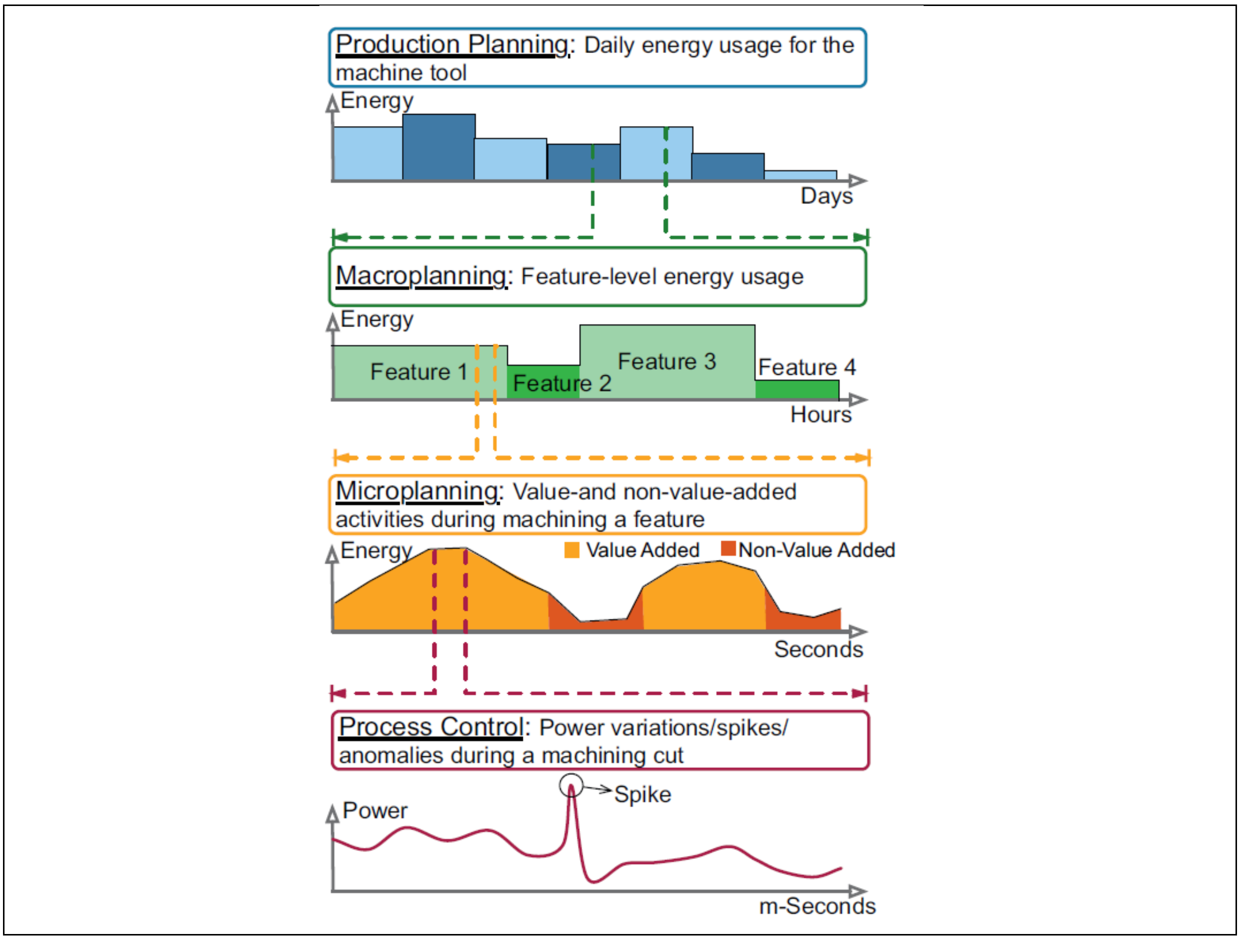


Figure 55: Examples of analysis across some of the temporal scales.

Vijayaraghavan has used event stream processing techniques to automate the monitoring and analysis of energy consumption of a manufacturing system. Events are point of interest as a function of a time. In manufacturing systems, events can be a numerical value (e.g. instantaneous power consumption) or type of annotation (e.g. the alarm state of the machine tool). The simple events are used to form complex events. As an example: based on simple events pertaining to the tool position, the instantaneous power consumption, and the machine tool's alarm state, a complex event indicating that the machine tool's spindle has crashed can be created.

Events stream processing techniques include rules engine (RE) and complex event processing (CEP). These techniques can be used to create higher level abstract events and reason on them by pattern matching and identification. A common algorithm implemented in RE/CEP systems is the Rete algorithm. The Rete algorithm provides a very efficient way of matching patterns by ‘‘comparing a large collection of patterns to a large collection of objects’’. One approach to pattern matching involves testing each rule against each event (or set of events) in the stream. More developed algorithms – such as Rete - algorithm uses a tree-structured sorting network to index and match patterns, avoiding computationally expensive iterations. The system can be used environmental analysis and optimization for complex manufacturing systems, where decision making is required across multiple levels of abstraction.

4.3 MODELS FOR COST ESTIMATION OF MANUFACTURING

The key element of the manufacturing operations is the cost. The definition of costs is related to the economic resources (manpower, equipment, real facilities, supplies and all other resources) necessary to accomplish work activities or to produce work outputs. Models for cost and time help to optimize at a rough level the process efficiency. In manufacturing operations there is always a balance between cost, quality and time used for manufacturing. In some cases it may be feasible to produce the components so fast as possible in order to save energy because only a minor part of the energy is related straight to the manufacturing operation (e.g. material removal with a cutting tool). In the next chapters cost functions and time functions for sheet metal manufacturing and milling are presented.

4.3.1 Sheet metal manufacturing

General

For the production of sheet metal components, a number of different production processes are available. Typical sheet metal production operations are: cutting, joining bending and finishing (Figure 56). A typical characteristic of sheet metal manufacturing is nesting. Nesting has a large impact on the execution of many engineering tasks, such as process planning, production planning and cost estimation.

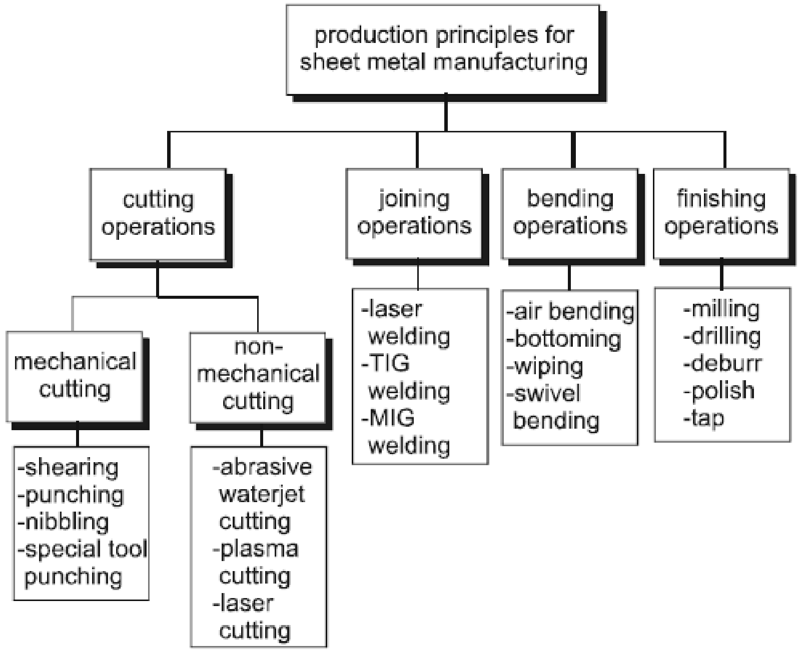


Figure 56: Overview of the most common sheet metal production process

Shearing

Blanks of suitable dimensions are cut from larger sheets or a coil by means of shearing. In shearing operation two blades are used. Shearing involves the application of shearing forces to rupture the metal. The shearing process is seldom mentioned in literature related to cost and time functions.

Punching

In punching, press pushes punch against and into the die and cuts a hole in the sheet by means of shear stresses. In Brinke and Vin five types of cost variables are distinguished for punching: machine time, labour, material, storage and transport. The model includes only the direct manufacturing costs. The processing costs are the sum of:

- machine running costs,
- labour costs,
- machine set-up costs and
- tooling costs.

The total processing time (Appendix 1, equation A.1) is the sum of the punching time (equation A.2), tool change time (equation A.3) and traversing time (equation A.5). In the case a sheet consists of parts from several batches, the number of tool changes has to be divided over the batches. Equation A.4 splits the number of tool changes based on the number of different parts. This estimated sharing ratio is also used to divide set-up and tool load times. The traversing time (equation A.5) is based on a non-optimal Zigzag-traversing pattern.

Nibbling

Nibbling removes material with a punch and die. The shape of the material removed is determined by the punch and trajectory of the tool. Material is removed with a punch by making a number of subsequent, partially overlapping punch strokes.

The processing time for nibbling has been derived. The equations for punching for tool change time (Appendix 1, equation A.3), number of tool changes (equation A.4) and traversing time (equation A.5) are the same for nibbling. The total processing time and nibbling time are calculated with equation (Appendix 2, equation A.6) and (Appendix 2, equation A.7).

Also time and cost functions are derived for nibbling. The total processing time is the sum of the set-up and work piece time (Appendix 2, equation A.8). The work piece time is the combination of the main time and the auxiliary time raised by 5% for personal care. The main time includes:

- time to go to the start position
- punching times
- traversing times
- tool change times

A distinction is made between punching of holes, nibbling straight contours and curved contours. The auxiliary time includes fixing and unfixing times and the time for scrap removal.

The costs are split up in fixed costs, variable costs and technology dependent costs (Appendix 2, equation A.18). The fixed costs rate includes depreciation of the machine and the space that the machine occupies (equation A.19). The rate for the variable costs contains the costs for energy, labour, maintenance and programming (equation A.20). The tool costs are considered to be technology dependent costs (equation A.21) (the material costs are not considered in this equation because comparison between nibbling costs and laser cutting costs are made).

Special tool punching

Special tool punching is similar to punching. However in this case no material is removed but only locally deformed. It seems that in literature, no specific time and cost functions are derived for special tool punching. Because of the similarity with punching, time and cost functions for punching could be used. There are also time and cost functions for non-mechanical cutting. Some of the functions are mainly cutting process independent (Appendix 3).

Bending operations

There are several types of bending processes e.g., bottoming, air bending, wiping and swivel bending. In the bottoming process, the bend is fully determined by the punch and die. This means that suitable punch and die combinations are dependent on sheet thickness, radius and material. In air bending using one combination of punch and die, it is possible to bend sheets of different thickness and different bend angles. Air bending requires relatively low press force. Air bending process is a very flexible bending process. Wiping and swivel bending are mainly used to create flanges. In [REF] actual bending, shoving, turning in the X-plane, turning in the Y-plane, turning in the Z-plane are considered as the main operations for bending (Appendix 4, equation A.60). In [REF] time functions for automatic (equation A.61) and manual (equation A.62) bending are derived based on a time study of the fabrication of two different frames.

A schematic process cycle of hydraulic press-brakes is presented in Figure 57. For a single bending cycle a distinction has to be made regarding the following phases:

- tool approaching the work piece with a power consumption on the stand-by level
- actual bending process with elevated power consumption
- return movement of the tool

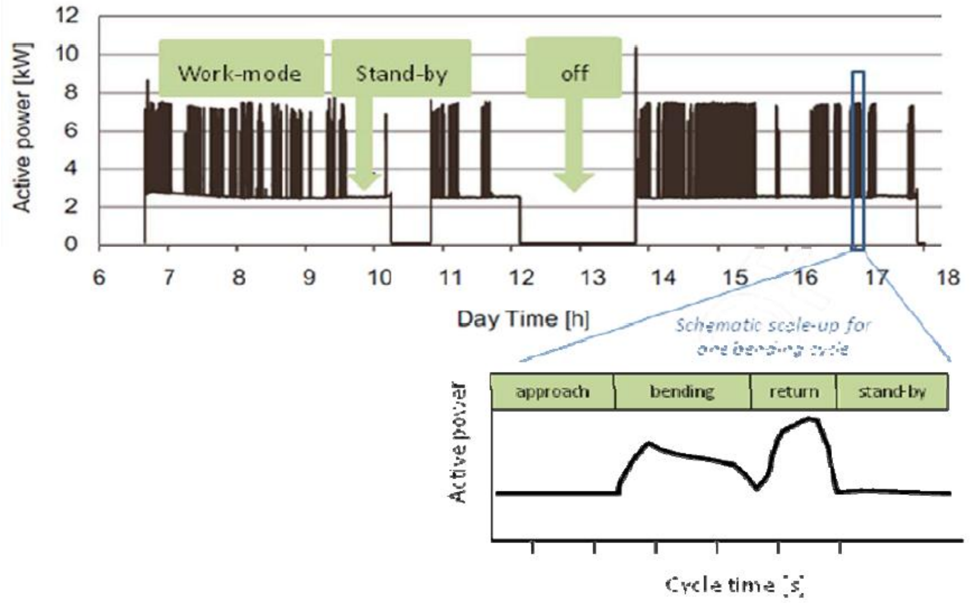


Figure 57: Power consumption cycle of press-brakes (note the high "return" value: in the same reference remarkable lower value is also given)

The overall power consumption of press brakes is presented in [REF]. For three hydraulic press brakes of a bending capacity of 110 t the reference state work mode (approach / bending / return cycle) power consumption of 2-6 kW, stand-by (e.g. during workpiece change and fixing) power consumption of 1.5-3 kW, and off-mode values of maximum 0.5 kW. The actual use power consumption depends on throughput and is in such a good candidate for optimization, i.e. cycle times and thus relation between work mode and stand-by times, the latter including load/unload times.

4.3.2 Machining

Vijayaraghavan et al. [81] demonstrates the application of the energy monitoring and analysis framework using energy consumption and process parameter profiles from machining experiments. A simulated energy profile is developed based on measured data (from the end-milling of aluminum using a 2-flute carbide cutter in a 3-axis precision milling machine). The simulated profile extrapolates the laboratory measurements to an industrial case. The spindle occupies three states during this profile: idle, low and high. The operational states of the machine tool include startup, shutdown, idle, and in-cycle. The analysis framework is applied in automatically detecting phenomenon pertaining to relationships between energy and operational performance of the machine tool. The specific events identified by the analysis framework, the energy and spindle profiles are shown in Figure 58. The events are discussed in Table 12.

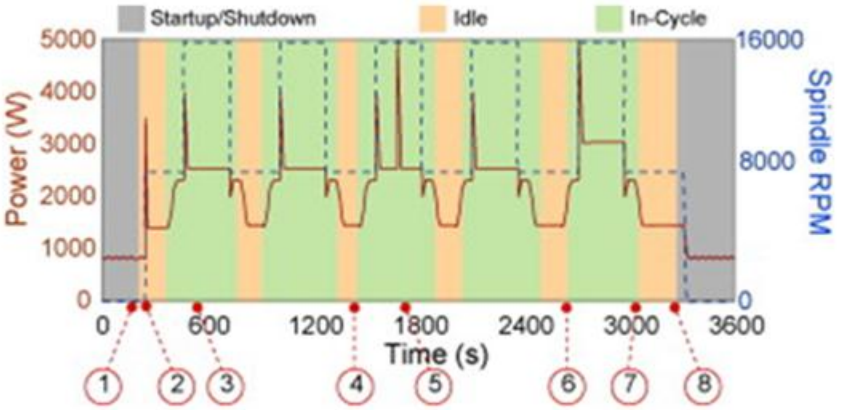


Figure 58: Energy consumption and spindle rpm profile for a case study

Event	Time	Reasoning
Machine idle	242s	Average energy use < idle threshold; spindle speed = 0
Expected energy spike	243s	Spike due to spindle startup (0-8000 RPM)
Expected energy spike	464s	Spike due to spindle speed increase (8000-16000 RPM)
Idle energy constant	1457s	Previous two idle periods energy use constant at 124kJ
Anomalous spike	1679s	Energy spike unaccompanied by shift in spindle RPM. Potential failure in spindle.
Idle energy increase	2612s	Current idle period energy use (211kJ) > Past idle period energy use (124kJ)
Part energy higher	3074s	Current part energy (1218kJ) > Previous parts average energy (1087 kJ)
Idle energy trend	3309s	Idle energy increasing monotonically over past two periods (324kJ > 211kJ > 124kJ)

Table 12: Event reasoning case study

There are also overall simulation programs for simulation of machining. This reference proposes machining simulation system that utilizes high-level data in order to produce a simulation. The system utilizes STEP and STEP-NC data model. The status-quo of the machine tool is captured by means of sensors to provide true data values for machining simulation purposes. The system provides three different modes of machining simulation process; Pre-Machining, Machining Simulation and Post-Machining that can portray all-inclusive simulation of machining operations.

There are also available cost calculators for making quotations. In [REF] a quotation Calculator program for cost estimation of turned components is developed. The system is connected to the machining module in CATIA V5. The calculator takes the main important factors into account but e.g. the cost of machining does not explicitly include the energy used for the turning process (but may be implemented in an average value).

4.4 MANUFACTURING SIMULATION MODELS

4.4.1 Punching/blanking process

There are several models developed for punching in open literature. In [REF] modeling of punching/blanking has been studied focusing on the effect of material properties on the calculated punching forces. The reference makes use of an analytical model, finite element simulations and a program of experimental verification. The analytics model for the punch force is based on the work of Atkins. Atkins derived the punching force F with friction modeled through an assumed proportion f of the shear stress and equations have been presented at the paper.

$$F_{punching}(d) = \psi(d)\pi D_p\tau((h_0 - d) + 2fd) \qquad (14)$$

D_p = diameter of the punch

h_o= thickness; see Figure 59

d= punch penetration, see Figure 59

It is assumed that the shear strain γ for pure shear can be used to estimate shear stress from the power law

$$\tau = C_1\gamma^n \qquad (15)$$

C1 was converted from the value of C2 in the power law

$\psi(d)$ is a correction factor for the punching force

$$\bar{\sigma} = C_2\bar{\varepsilon}^n \qquad (16)$$

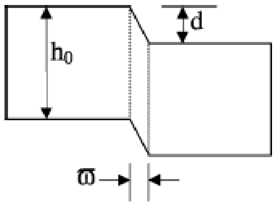


Figure 59: Simple flow during punching/blanking

The study also describes finite element modelling of punching/blanking. The finite element model uses modified Gurson's yield criterion (preferred over Lemaitre's damage criterion). The relationships defining Gurson's yield criterion are expressed in terms of the void volume fraction: υ. υ is defined as the ratio of the volume of voids to the total volume of the material. For metals containing a dilute concentration of voids, the yield criterion is proposed according to Eq. (4). It is based on a rigid plastic upper-bound solution for spherically symmetric deformations of a single spherical void:

$$\Phi = \left(\frac{q}{\sigma_y}\right)^2 + 2q_1\upsilon cosh\left(-q_2\frac{3\sigma_m}{2\sigma_y}\right) - (1 + q_3\upsilon^2) = 0 \qquad (17)$$

with

$$q = \sqrt{(3/2)S{:}S} \qquad (18)$$

is the equivalent von Mises stress,

$$S = \sigma_m I + \sigma \qquad (19)$$

the stress deviator, with σ_m the hydrostatic pressure, $\sigma_y\left(\bar{\varepsilon}_m^{pl}\right)$ the yield stress of the fully dense matrix material as a function of $\bar{\varepsilon}_m^{pl}$, the equivalent strain in the matrix. Values for the constants q1, q2 and q3 (coefficients of the void volume fraction and the pressure terms) are given in the reference.

On the basis of the results of the study the maximum punching force in the finite element simulations of the cold rolled steel increases with a decreasing clearance in a similar trend to the experimental data. The FEM –calculations show that the model using the tensile test data appears to predict values for the maximum force which are below the values found during experiments. The stress–strain data obtained from in-process measurements produce higher values of the maximum punching force and edge draw-in than the stress–strain data obtained from tensile test results. There are many publications in open literature aiming at to model fracture in punching/blanking. For example, recognising that the large plastic strains lead to nucleation, growth and coalescence of voids and thus to a weakening of the material.

Speed of the process has an effect on the quality of the product and life time of the tool. [REF] aims at to estimate the effect of speed of the punching/blanking process on the quality and punching force (and the life time of the tool). Increase of the speed of the blanking-punching -process does not lead linear increase of force: the speed of the process should be carefully chosen when tool life is considered.

4.4.2 Bending

The sheet bending is a process that needs careful preparation because of the spring-back of the bended sheet.

Analytical and numerical methods for calculation of bending and spring-back have been presented. There are numerous publications related to the numerical bending and spring-back simulation. In [REF] a survey of a computer aided process planning of sheet metal bending is presented.

The needed energy for bending can be approximated on the basis of forces, displacements and time needed for the operation. Analytical equations for bending forces are presented in [REF]. The bending can usually be approximated as simple beam bending. Thus, the bending force is a function of the strength of the material, the length and thickness of the piece, and the die opening. For example the equation for forces in V-bending is as follows (Figure 60):

$$F = \frac{4M}{I_k - 2(R_k + R_t + T)\sin\frac{\varphi}{2}} \cos^2\frac{\varphi}{2} \qquad (20)$$

Where I_k is the die opening and φ is the bend angle.

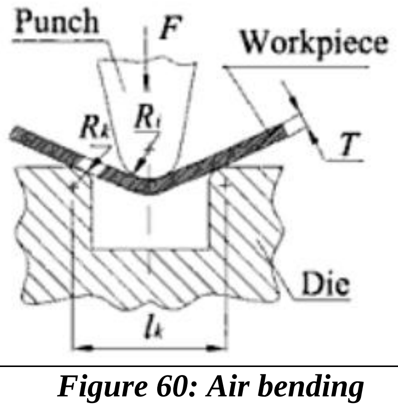


Figure 60: Air bending

4.4.3 Machining

Machining can be simulated by means of numerical (FEM) programs or analytical programs. Analytical models give a rough estimate e.g. cutting forces. Analytical models are usually simple but advanced numerical can include e.g temperature effects and the effect of tool wear.

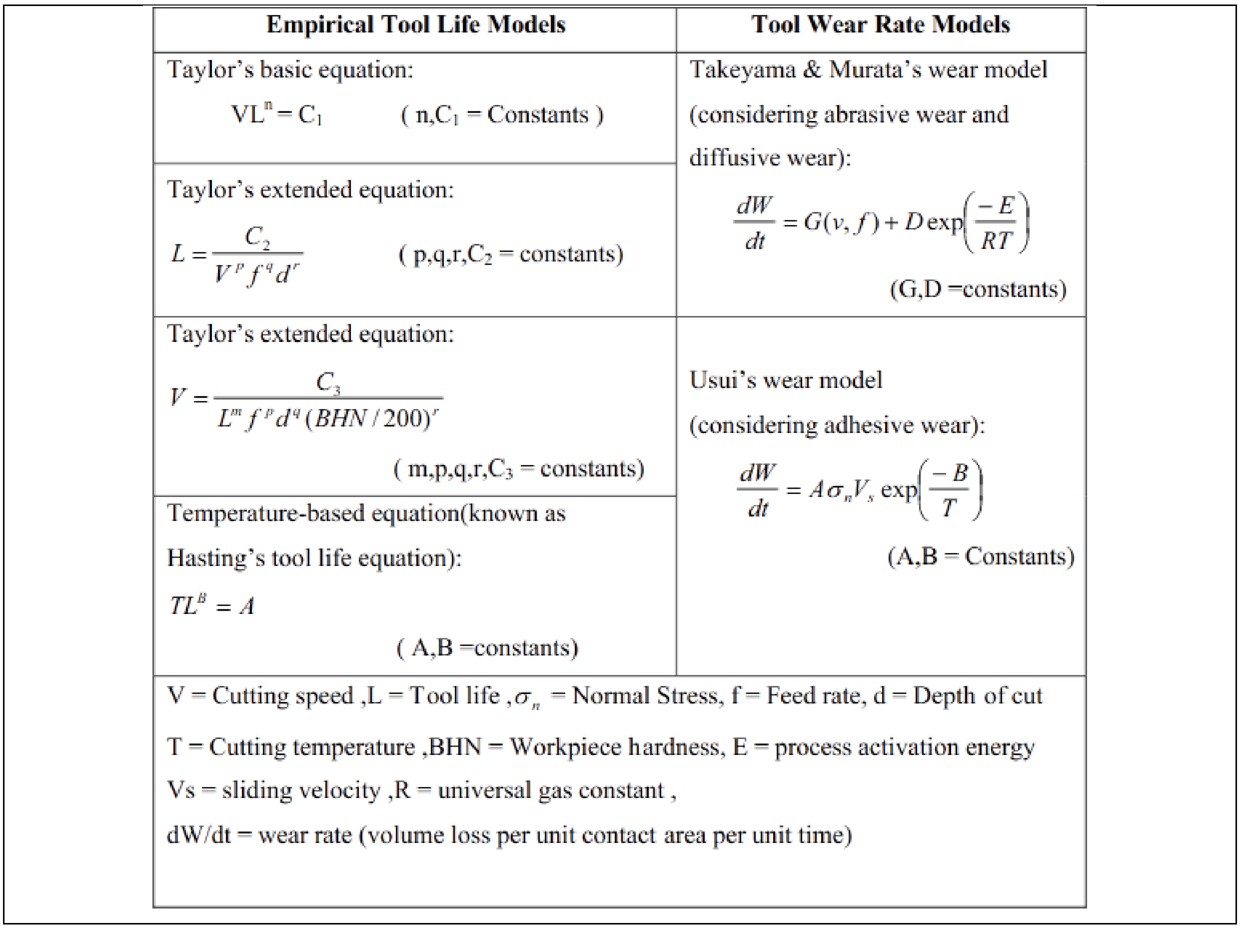
The numerical models need accurate material data and suitable material models. There are material models suitable for simulation of machining that take into account e.g. strain rate effects. In addition to programs that are working in narrow specific application there are also complete modelling systems aimed at to evaluate the energy consumption of a machine tool system for part machining. The study presents an analytical approach for the estimation of the variable mechanical energy requirements of machine tool systems with experimental verification. The model takes into account:

- the machine tool layout
- moving masses and spindle and feed axes specifications
- the cutter location data and the cutting force values in end milling
- the process time calculated based on feed kinematic profiles and command variables control

The energy estimation, based on cutter location data and speed values from an APT file as well as on specific characteristics of the spindle and feed axes and a cutting force module, was experimentally validated.

4.4.4 Tool wear models

There are several publications in the open literature related to tool wear in punching, blanking, stamping, shearing and machining. Abrasive toll wear in metal forming is presented in [REF]. Tool wear model in punching and in blanking are presented in [REF]. Wear models in stamping are presented in [REF]. Tool wear models in shearing are presented in [REF]. Mathematical models are developed also to describe machining tool wear in quantity. They can be categorized into two types: tool life models and tool wear rate models. Survey of available models is presented in Table 13.



Empirical Tool Life Models	Tool Wear Rate Models
Taylor's basic equation: $VL^n = C_1$ (n,C_1 = Constants)	Takeyama & Murata's wear model (considering abrasive wear and diffusive wear): $\frac{dW}{dt} = G(v,f) + D\exp\left(\frac{-E}{RT}\right)$ (G,D =constants)
Taylor's extended equation: $L = \frac{C_2}{V^p f^q d^r}$ (p,q,r,C_2 = constants)	
Taylor's extended equation: $V = \frac{C_3}{L^m f^p d^q (BHN/200)^r}$ (m,p,q,r,C_3 = constants)	Usui's wear model (considering adhesive wear): $\frac{dW}{dt} = A\sigma_n V_s \exp\left(\frac{-B}{T}\right)$ (A,B = Constants)
Temperature-based equation(known as Hasting's tool life equation): $TL^B = A$ (A,B =constants)	
V = Cutting speed ,L = Tool life ,σ_n = Normal Stress, f = Feed rate, d = Depth of cut T = Cutting temperature ,BHN = Workpiece hardness, E = process activation energy Vs = sliding velocity ,R = universal gas constant , dW/dt = wear rate (volume loss per unit contact area per unit time)	

Table 13: Tool life and tool wear rate models

4.5 ROBOTS AND HANDLING EQUIPMENT SIMULATION TOOLS

Process and product simulation software is used for the verification of the assembly process and the product itself. Graphical representation of the assembly equipment, product components and workcell are used to identify problems during process and product design. DELMIA's V5 DPM Assembly is designed to optimize both process engineering and the assembly manufacturing process by enabling users to author, simulate, and validate the manufacturing process plan when it is most productive and cost–effective, in the planning stage, long before equipment is installed or moved inside the plant. This tool facilitates concurrent design and manufacturing, assembly feasibility studies, manufacturability studies, serviceability studies, 3D process planning, and authoring of assembly process specifications. It allows users to capture assembly process information in a way that is re-usable to leverage information across products and across the extended enterprise. V5 DPM Assembly has the ability to simulate parts, assemblies, devices, and robots. Additional solutions provide simulation support for other types of entities, such as human models and NC machines. Tecnomatix ROBCAD is another simulation package which enables process simulation and verification.

Figure 61: DELMIA V5 DPM ASSEMBLY – 3D Visualization [92]

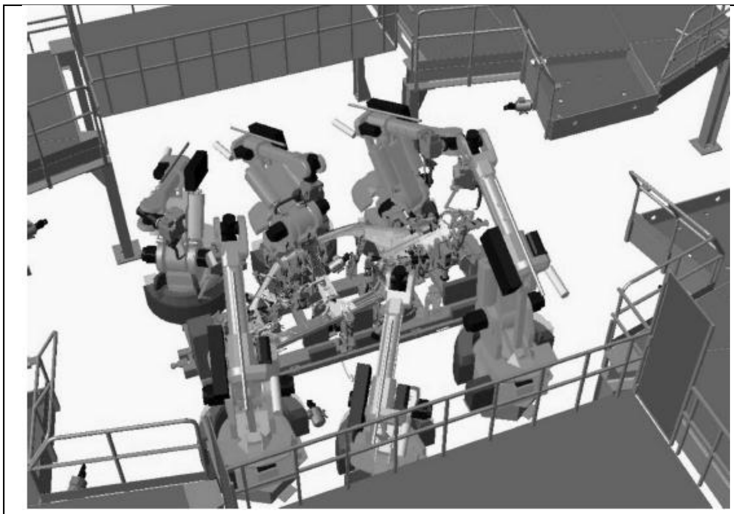


Figure 62: Simulation of robot welding with Tecnomatix ROBCAD [93]

4.6 ROBOTICS SIMULATION

A robotics simulator is used to create embedded applications for a specific (or not) robot without be dependant of the 'real' robot. The underlying concept is to design, simulate, optimize, and program robotic workcells in a 3D digital factory environment. Tooling definition, workcell layout, robot programming, and workcell simulation are among the most widely used functionalities. In some case, these applications can be transferred on the real robot (or rebuilt) without modifications. Robotics simulators allow the representation and evaluation of robot cells and task that would otherwise be very demanding in terms of cost and time. Kinematics and dynamic analysis are some of the features offered by state of the art robotic simulation tools such as ROBCAD, DELMIA etc. A list of the features included in such tools is presented below:

- Interoperability with major MCAD systems
- Robots, machines, tools, equipment libraries
- Modeling of components
- Modeling of complex kinematics of robots and other mechanisms
- 3D layout definition of workcells
- 3D path definition with reachability check, collisions detection and optimized cycle time
- Motion simulation and synchronization of several robots and mechanisms
- Modeling and optimization of the whole manufacturing process SOP (Sequence of Operations)
- OLP (Off-Line Programming)
  - Optimized programs downloaded to robots on the shop floor
  - Up-loading existing production programs for optimization
- Open architecture for customization/extension
- Resource kinematic and logic modeling
- Ability to edit in context for tooling resources
- Automatic interference zone computation
- Automatic weld feasibility analysis at the workcell level
- Drag and drop, direct manipulation, and table-based task editing
- Standard library containing over 700 accurate robot models
- Realistic robot simulation (using the optional RRS I and RRS II AOPs) support for accurate trajectories and cycle times
- Cell and robot calibration for accurate downloads
- Professional CAD capabilities
- Comprehensive multi-CAD interfaces

Major benefits expected from the use of such simulation packages involve but are not limited to: Increase manufacturing quality, accuracy and profitability, Reductions in labor-hours and process engineering lead time, improvement of program accuracy and process quality, optimization of development and capital investment, better use of production equipment (OLP), reduction of product costs and acceleration of time-to-market.

4.6.1 Programming of industrial robots as an application of process simulation

Every movement and each activity of a robot have to be programmed before the robot can work. To program it there are three different types of methods to use: online programming, hybrid programming and offline programming (with the help of process simulation). In future robots will use their sensors and setup intelligence to learn, act and serve independently. Controlling a robot offline or online using software gives a high flexibility. And this is attributed to the fact that programming of the robot control is carried out away from the work cell. There is no loss of time since production can go on during the programming process. Another advantage is the extensive rationalization potential due external computer systems which are more human and safer to use than robots. The most widely used computer applications for this kind of programming are textual and graphical.

Online Programming

Online programming is a method to program the industrial robot directly. There are two different techniques: Playback and Teach-In. The Playback method is a manual leading of an end effector with a simultaneous recording of all axial positions in a fixed clock pulse. The speed is given manually. There are several problems with the Playback method which should be attended. The working cell of the robot needs high safety requirements, because of the manually guidance of the effector. The robot also needs the ability to move all its servos manually. Another problem is that if there shall be a change in an individual course section the whole course has to be repeated.

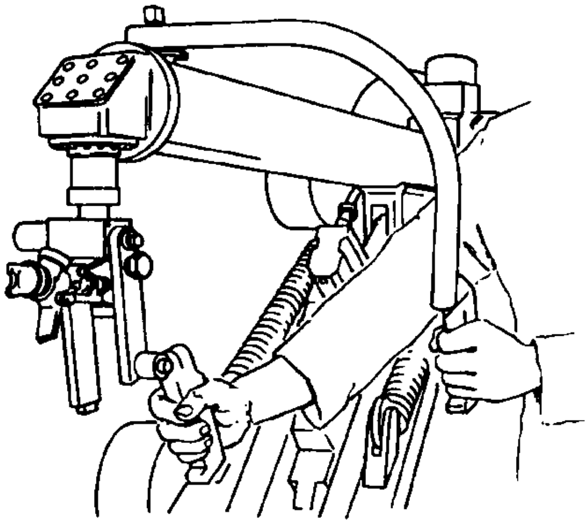


Figure 63: Online Programming with Playback

Teach-In is a manual guidance to the end position of the end effector with a hand held programmer like individually with keys or simultaneously with joystick or 3D/6D mouse. After adjustment at the end position and orientation, the positions of the robot are stored. This storage of the end position of the effector can be a problem, because there is no description about how the robot shall move to this position. The movement to the end position can differ each time.

Offline Programming

The robot program is made externally by using a special robot programming language which is different for each robot manufacturer. Most times if there is a working plan for a robot, it has to be adjusted for a robot of a different brand. A robot programming system can be text based or can be with a graphical surface which allows simulation of the robot movement. The process simulation can be in real time, in a virtual environment and with a realistic physic.

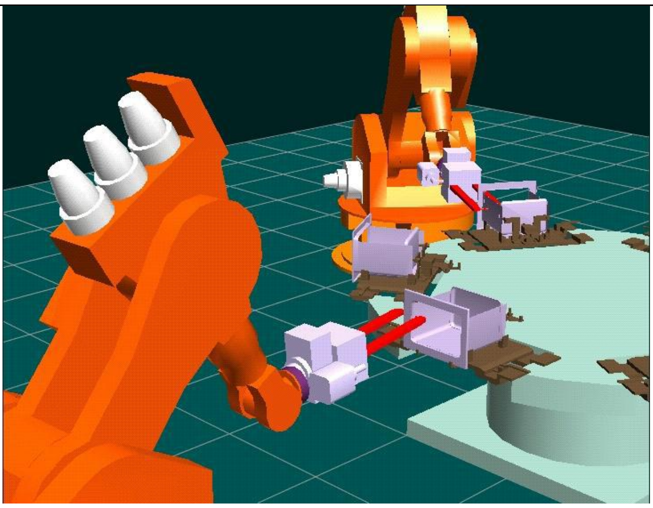


Figure 64: Example of Offline Programming

Hybrid Programming

Most times hybrid programming of a robot is used to change and optimize offline programmed robot paths in a continuous production. The input of the correction values are done with a text or graphical system without any kind of simulation. Hybrid programming is mostly used to change the orientation of robot tool. The whole programming can be done without halting the production process.

Comparison of In Process Programming and Off Process Programming

In the following table 14 in process programming and off process programming are compared to each other. In general the online programming presents a number of limitations. The production has to be stopped and there is only a simulation on a real system. In offline programming there is a simulation which also allows simulating with different environments like cold and hot temperatures. With off process programming whole manufacturing lanes can be designed and simulated before they are built. The future industrial robot programming has the employment of more capable 3D offline programming systems which are integrated in production data management systems.

In Process Programming		Off Process Programming
Real	**Robot system and Equipment**	Model
Available	**Equipment availability during programming**	Not available
On real system	**Program Testing**	Through simulation
Limited	**Accessed Operational Information System**	Full integration possible
Program quality dependent upon its experience	**Requirements of the Programmer**	Support by intelligent, computer based means

Table 14: Comparison of In Process Programming and Off Process Programming

Process of programming a robot

The programming process of a robot has several steps. First the designer has to choose a working cell and a suitable robot to carry out the future work. Different working processes need different types of robots. The next step is to create a virtual working cell for further simulations. After important points are stored using the Tech-In procedure. With these points taken in reality an offline program is created. Following there is realistic simulation with different properties and environments. In this step the program can be optimized and easily changed. Later than the robot is setup with the created program. If there has to be a changing of the robot program the input can be done directly on the robot.

1. Offline Programming (using Teach-In procedure)
2. Online Programming (creating and simulating the robot program)
3. Hybrid Programming (changing and optimizing the robot program)

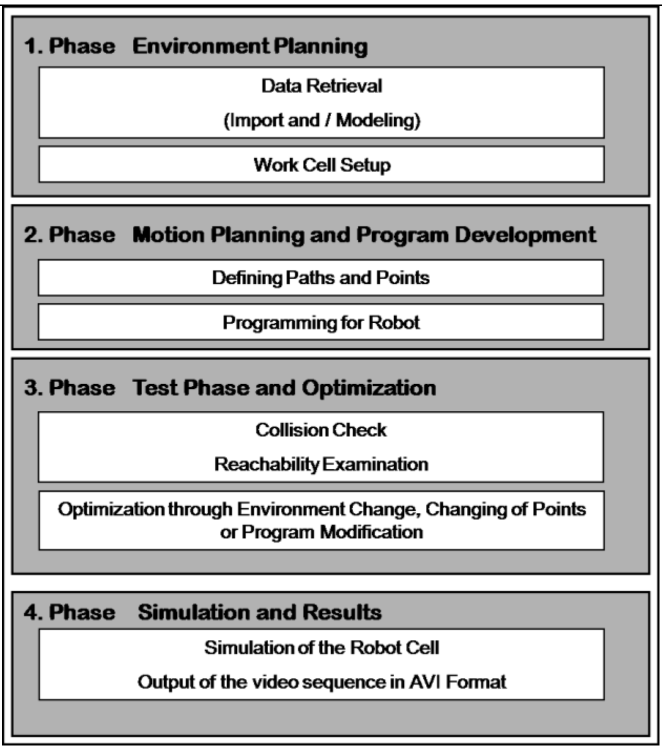


Figure 65: Procedure for the preparation of Simulation

4.6.2 Simulation model of robots and their environment for process simulation

The Offline programming of robots is normally concerned with a work piece oriented programming in a 3D environment. The 3D motion simulation of robots is based on the model with a robot in a cell, which basic modules are geometry, kinematic and a control model (GKC model) as seen in Figure 66.

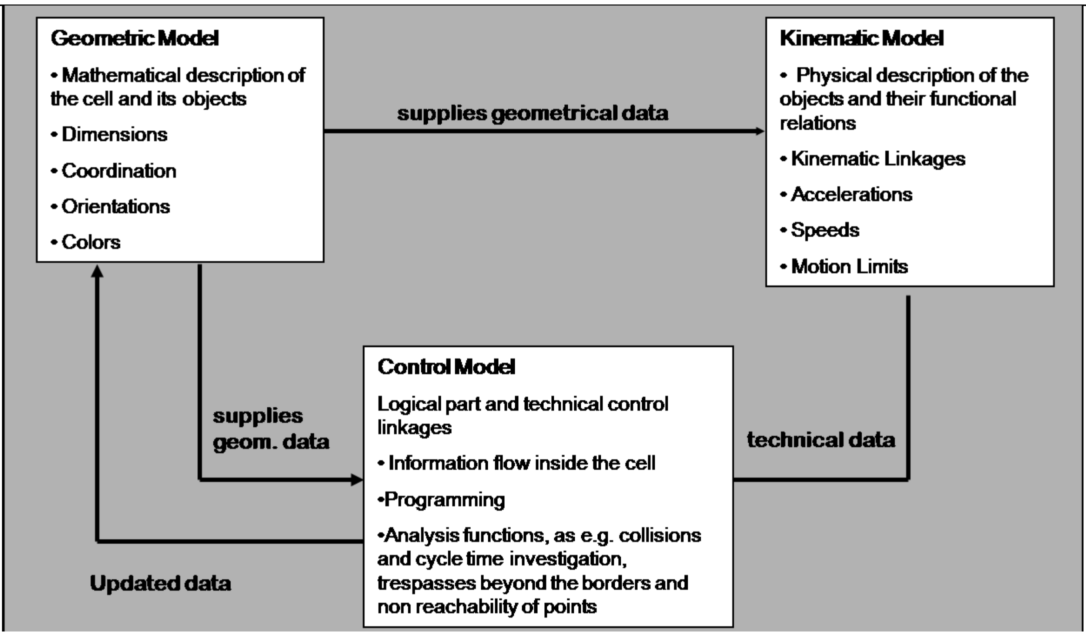


Figure 66: Schematic Relationship of the GKC Model

Geometry Model

The geometry model contains the dimensions of the entire work cell and individual devices. It describes the 3 dimensional areas and its contained objects mathematically. These can be production technical devices as for example, the robot, tables, shelves or conveyors. In addition all data of work pieces are also contained in this model, so that the geometry model represents the work cell optically.

Kinematic Model

The kinematic model is concerned mainly with physical and technical data of the work cell. In addition the kinematic relations between individual parts of the complex devices are also included; for example joint relations of the robot. The additional machine attributes are such as acceleration, speed and axes limits therein. The kinematic model consists of purely 3D mathematical data of functionally connected devices and describes thereby their physical characteristics.

Control Model

The motion simulation and its components are included in the control model. It is concerned with the programming of the devices in the work cell, their control technical linkage and the information flow. The control model represents the logical unit of the cell.

Deviations of the IR Simulation from the Reality

Nowadays simulations can only simulate a few parameters of the reality (as seen in Figure 67). In the next years when computers will be more powerful simulations are expected to become more accurate. Tasks of the simulation are to simulate the robot control, sensors, operating attributes of the robot and position tolerances of individual objects.

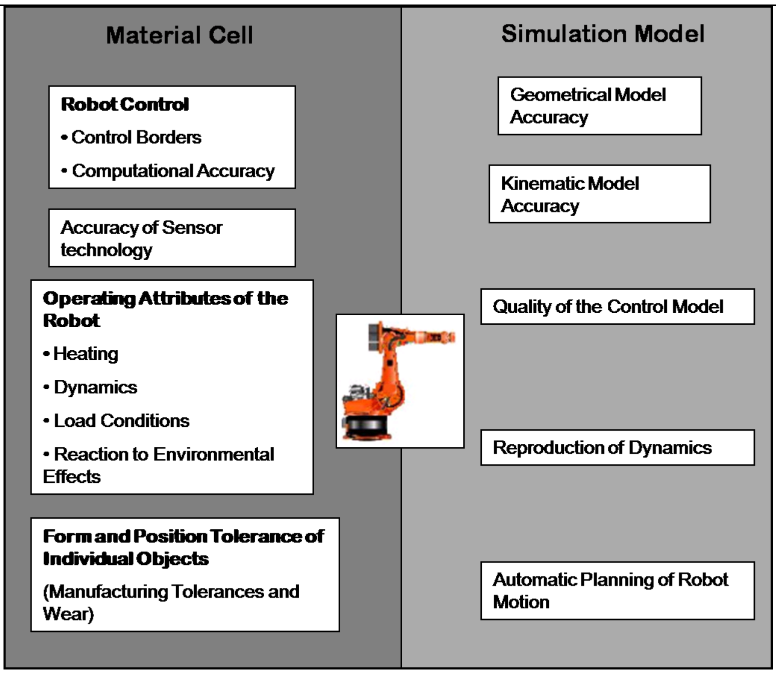


Figure 67: Deviations of the IR Simulations from the Reality

4.6.3 Robotic simulation tools

Specifically for the automotive industry which is characterized by the massive use of robots there exist several solutions incorporating robotic simulator applications. DELMIA, and ROBCAD are the most typical examples. Below a short description of each package is provided:

DELMIA

DELMIA V5 ROBOTICS is a powerful, integrated solution that enables manufacturing organizations to design, simulate, optimize, and program robotic workcells in a 3D digital factory environment. DELMIA contains numerous workbenches allowing for different simulation tasks and analysis. Below the tools that seem most appropriate for the ENEPLAN project are shortly described [94]:

DELMIA - Resource Layout DELMIA

Manufacturing Resource Layout allows end users to work efficiently on factory layouts; providing area reservation and advanced layout tools that can be used at various stages of the factory definition going from logical definition of the manufacturing concept to resource detailed design.

DELMIA - Manufacturing System Definition

DELMIA Manufacturing System Definition provides tools for the authoring of manufacturing systems and system structure and manual balancing of activities between systems including visualization of system inputs and outputs, product flow between systems, activities on systems, physical resources, and topology.

DELMIA - Workcell Sequencing

Workcell Sequencing is a powerful 3D simulation tool used to design and simulate manufacturing processes. It builds upon the workcell model developed in Robot Task Definition, Human Task Simulation, or DPM Assembly Process Simulation. With Workcell Sequencing, the user can coordinate and review the functioning of multiple resources as they work in tandem.

DELMIA - DPM Process & Resource Definition

DELMIA DPM Product and Resource Definition provides tools to allow process planners to author process and resource data, author process plan and product and resource assignment, and to define and verify assembly sequences.

DELMIA - Device Task Definition

DELMIA - Robot Task Definition enables organizations to design and optimize their manufacturing workcell layout. It deals with the "spatial organization" and components of the plant, allowing quick easy layout and downstream evolution of the layout design. The user may verify that the chosen robot is the most appropriate for the task using reach analysis, auto place, and feasibility studies. The user can then optimize robot layout and resource positioning. Robot Task Definition also provides tools to complete robot programming. The output of Robot Task Definition is a virtual model of the manufacturing cell, complete with Product and Resources as well as the process each Resource (i.e. robot) is required to perform.

DELMIA - 3D Simulation for Manufacturing

3D Simulation for Manufacturing (DMR) is an infrastructure product that provides basic simulation capabilities to DELMIA V5 applications. Products that include 3D Simulation for Manufacturing may be used to simulate parts, assemblies, devices, and robots. Further, such products may provide simulation support for other types of entities, such as human models, NC machines, etc.

ROBCAD

Tecnomatix Robcad enables the design, simulation, optimization, analysis and off-line programming of multidevice robotic and automated manufacturing processes in the context of product and production resource information. It provides a concurrent engineering platform to optimize processes and calculate cycle times.

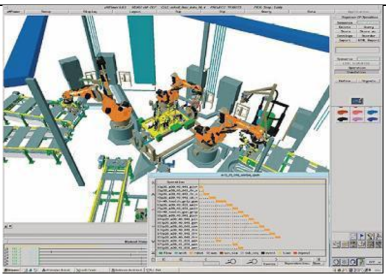


Figure 68: Screenshot from ROBCAD working environment

Key features of this simulation package involve: Workcell layout design and modelling, Motion simulation for robots and mechanisms, Collision, SOP (sequence of operations), OLP (off-line programming). Robcad OLP enables accurate simulations of robot motion sequences and the delivery of machine programs to the shop floor. Robotized processes that can be simulated within the ROBCAD environment involve:

- Spot welding
- Arc welding
- Painting
- Sealing
- Gluing
- Sand blasting shot
- Peening
- Flaming and thermal spraying
- Drilling and riveting

- Laser, water-jet and plasma cutting
- Polishing, grinding and deburring

http://doc.utwente.nl/40351/1/t000001d.pdf

5 R&D PROJECTS

PUBLICS EUREKA: The project regarded the development of the development of automated adaptive 3D laser cutting machine.

PAMELA EUREKA: The project was about the development of the 2D very high speed laser cutting machine with a redundant axis control system.

RESALT EUREKA: Development of remote laser spot welding system.

DIFACEC-FP6: Development of integrated platform for supply chain manufacturing.

MYCAR C-FP6: Development of high flexibility automotive manufacturing systems.

e-Custom EC-FP7: Development of web-based system for mass manufactured high customization industrial process.

ADMAP-GAS (Unconventional (Advanced) Manufacturing Processes for Gas-Turbine Engine Components): Development of a combination of Abrasive Waterjet Machining (AWJM) and Wire EDM (WEDM) processes.

COPERNICO (Co-operation Environment for Rapid Design, Prototyping and New Integration Concepts for the Factory of the Future): Survey detailing the range and capabilities of modelling and CAM tools available.

REFORM (Resource-Efficient Factory of Recyclable Manufacturing Composite Components): Measurement of the life-cycle costs of various materials and processes and then improvement of their eco-efficiency.

CAMEL- MCG (2010 - 2012): Development of highly efficient and environmentally friendly grinding technology through a minimum coolant lubrication approach.

ASPIRATE (2009 - 2011): Development of a new machining technology for carbon and glass fibre reinforced plastic (CFRP and GFRP) parts based on the internal extraction of the produced chip and dust particles through the whole machining system.

MAGFORGE: Magnesium Forged Components for Structural Lightweight Transport Applications (2006 - 2009): Development of tailored and cost-effective technologies for the industrial manufacturing of magnesium forged components.

PROLIMA: Environmental Product Lifecycle Management for building competitive machine tools. FP6 (2005 – 2008): The overall objective of PROLIMA, is to provide European machine tools manufacturing SMEs with means to develop machines with minimum environmental impact and optimized global life cycle costs, focusing on cutting based machine tools.

NOISELESS (2002 - 2005): Defining appropriate strategies for machine tool builders that combine simultaneously tool and structural modifications, and damping /absorbent devices in order to reduce noise emissions on machine tools.

ENGY (2002 – 2005): Development of low energy and eco-efficient grinding technologies focusing on improvement of the energy efficiency of grinding and grind-hardening.

SEPMAC: *Sustainable and Economic Production of Magnesium Components. (2000 - 2004):* Development of a new integrated system for ecologically sound High Speed Machining of Magnesium.

CoCoS: CBN Grinding of Crankshaft in one Set-up (1998 - 2001): Development of a single step, single set-up production of crankshafts on a single machine.

INTEGRITY: Integration of Heat Treatment into Machine-Tools by using Advanced Grinding Technology. (1997 - 1999): Development of machine-tool system concept suitable for grind-hardening.

LEPOCUT: Developing Less Pollutant Cutting Technologies (1996 – 2000): Development of cutting technologies t using minimal quantities of lubricant, without risking the quality of the final product.

Future developments

Currently specific requirements on machine tools have not yet been defined. Mandatory requirements specifically defined for machine tools may set limits such as the maximum energy consumption or restrictions in usage of auxiliary materials. Manufacturers will have to provide customers with information on the energy performance of their products and/or guidelines to help minimise their environmental impact during use phase. We can expect the application of these requirements as of 2012.

- ***Ecodesign directive 2009/125/EC***

This new directive affects to all the machines which are fabricated or installed in EU and has to be transcribed to specific regulations of all the different products. Product groups regulated under the ecodesign directive 2009/125/EC have to meet three criteria (Art. 15):

A. The product shall represent a significant volume of sales and trade, indicatively more than 200 000 units a year (...)
B. The product shall (...) have a significant environmental impact within the Community
C. The product shall present significant potential for improvement in terms of its environmental impact without entailing excessive costs, (...)

- ***CECIMO's proposal***

The Self Regulation Initiative (SRI) is CECIMO's response to the European Commission's plan on evaluating mandatory requirements for the metalworking industry. The machine tool industry prepares to commit itself, through a voluntary agreement with the Commission, to meet the energy reduction targets set by the ecodesign directive. CECIMO proposes the adoption of SRI (Self-Regulation Initiative) to "translate the objectives of the Directive in a more efficient and less costly way". Industries regulated by self-regulation will not be bound by mandatory requirements decided at Commission level. This method allows the machine tool industry (represented by National Associations) to define their own rules in the framework of the Ecodesign Directive, while structure, products and customer needs are taken into consideration. This means that the industry has a driving role in deciding how the directive will be implemented. Self-regulation gives machine tool builders the chance to choose the most appropriate technological option to achieve environmental performance objectives.

The intended goal of the SRI of the machine tool branch is to increase the ecological performance of machine tools while maintaining the freedom of innovative development, minimizing administrative burdens and clear positioning of advanced manufacturing against copycat.

The modular approach proposed is based on the idea that each machine tool should be seen as an individual product with its own environmental performance improvement potential. The basis of the method is a modular view of the machine tool. Theoretically the machine tool is split into its modules, i.e. components with specific and defined functions. In order to provide data in a common unit, manufactures will be supported by a calculator program and list of improvement potentials including quantitative values. The list of improvement potentials describes the measures which can be implemented into a machine tool for better environmental performance. The list will be regularly updated in accordance to innovations and technical developments.

This approach allows manufacturers to indicate the potential for energy improvement of a large variety of products without unnecessary comparison with any other competitive product. This ensures the confidentiality of information. This method gives each manufacturer the opportunity to declare their energy saving achievements by a product declaration.

- ***ISO working group***

CECIMO Energy Efficiency Working Group and EuP Steering Committee are responsible for the preparation of the SRI within CECIMO. An ISO Working Group under ISO/TC39 dealing with the environmental evaluation of machine tools was created following the initiative of CECIMO members. Compliance with the new ISO standard which will come out of this Working Group is an integral part of the SRI methodology.

- ***BLUecoMPETENCE initiative***

VDMA ((Verband Deutscher Maschinenund Anlagenbau – German Engineering Federation) has published its sustainability initiative called BLUecoMPETENCE. The initiative is financially held by the German government and is created to develop sustainable technologies in the machine tool sector. With BLUecoMPETENCE, the aim of the VDMA is to emphasize the mechanical engineering industry’s capability to provide sustainable solutions, actively promote and offer sustainable technologies, and to create sound, consistent, and solid criteria and standards for sustainable production and products.

On this basis, the BLUecoMPETENCE trademark establishes transparency, orientation, and reliability. Companies that join the initiative commit to implement sustainable ideas and concepts, develop solutions, and achieve goals.

The BLUecoMPETENCE is oriented not only to customers, suppliers and other market partners but to the representatives of the political sphere, media, research and education sectors, capital and labour markets and to the broad public. Due to its success the BLUecoMPETENCE initiative is being studied to be applied in the CE.

6 CONCLUSIONS

6.1 *MILLING*

Main problems

- High cutting forces result in low stability of the process.
- Problems occur mainly because of the vibration.
- Vibration can affect the machine guidance or the cutting tool can break and the quality of the work-piece surface can decrease.

Energy consumption in milling process

The major share of a machine tool's energy consumption is load-independent and used by peripheral equipment, with the chip removing energy having minor impact on the total energy consumption. Auxiliary components with a constant load and power consumption fulfil essential functionality but without proportionality to added value. Their power consumption must be limited to the essential physical minimum.

The spindle unit energy consumption increases as long as material is removed from the workpiece. More relevant than the sole spindle power is the specific spindle power consumption e_s, which describes the efficiency of a cutting process; a lower e_s means a higher efficiency. Experiments pointed out that the specific spindle power consumption e_s is significantly influenced by:

- cutting speed (V_c)
- feed per tooth (f_z)
- depth of cut (a_p)
- width of cut (a_e)

The specific spindle power consumption usually declines with increasing these parameters. This fact explains why high-feed end mills have better energy efficiency. On the other side, the situation can be different if the process becomes unstable: as the spindle copper losses are proportional to the root mean squared value (RMS) of the torque, the presence of a dynamic component in cutting force may cause an increase of e_s. Therefore, a_p and a_e over certain levels could be disruptive from the efficiency point of view. Moreover, other environmental issues and energy consumers should be addresses, like the following:

- *Coolant:* It is suggested that using coolant at all may not be completely necessary.
- *Air Pumps:* Air is constantly pumped into the machine. Parts are also often washed down with air, and this could probably be done by hand or water.
- *De-mister:* Such a vast amount of mist can be accumulated by the heat and coolant of the machining process, that it can be necessary to attach a de-misting device to the machine. This obviously uses energy and costs money.

Eco-Friendliness

- *Swarf and general wastage:* Swarf is very easily controlled and recyclable.
- *Hazardous gas:* A lot of the hazardous gas is removed by the de-misting device.
- *Liquid waste:* The bulk of liquid waste is the coolant required to aid cutting. Most machines have a system whereby coolant is drained from the machine, then re-used or recycled.

What can be improved?

- A device that shut down the power of different axles while not in use would be useful.
- Alternatives to coolant could be implemented into the machines, or a system that encourages re-using of the coolant and prohibits waste as much as possible.

- Machines could be made even more flexible, so as to machine an even wider selection of parts.

6.2 PUNCHING

Energy efficiency of punching

Punching processes are very energy efficient, compared to alternatives such as laser cutting and milling. Losses on such machines are:

- Heat produced by the rapid plastic deformation of the material when sheared.
- Frictional losses in gears, slides and eccentric shafts.
- Limited efficiency of power sources.
- Leakages in hydraulic and mostly pneumatic systems.
- Pneumatic systems require filters and air dryers which consume additional energy.

As presses need to exceed maximum force only at a limited portion of their movement, KERS (Kinetic Energy Recovery Systems) have lately been incorporated in such machines in order to increase their efficiency by storing energy when braking and using it to the next work stroke.

What can be improved?

Any efficiency improvements on the punching processes should come from:

- An improvement of the power source efficiency (AC electric motors/Servo motors/Pumps/Compressors).
- A reduction of frictional losses.
- Regeneration of kinetic energy to use it on the next stroke
- Regeneration of the heat produced during punching to heat water or to create electricity.

Open points/problems

- Energy consumption is measured relatively easy, but phase of work energy is used should be identified.
- What parameters should collect from the machine?
- It would be good to create an algorithm that can calculate a number of different variables on the basis of actual consumption.
    - Power consumption
    - Material utilization rate
    - Tool wear etc.
- Values of input parameters which cannot be measured should be determined, i.e. salaries, rents, etc.
- The machine maintenance necessary to set automatically on the basis of the measured values.
- How can the machine take advantage of waste heat for space/hall heating?

6.3 FORMING (PRESS)

The main advantages of metal forming are the following:

- High productivity
- Low cost per part
- Low scrap material and energy consumption
- Quality of formed parts.

Problems and efficiency considerations on forming presses are similar to the ones used for punching presses (see above).

Future developments

The objective to improve production costs is pursued through:

- Process & manufacturing simulation to identify areas of inefficiencies.
- Integration of all machines belonging to the same production line (material and data flow)
- Close attention to the complete manufacturing cycle, also through the supply of added high-value services (turn-key project design) and analysis of tasks before and after the forming process itself (welding, bordering, specific material alloys supply, etc)

6.4 EXTRUSION

Average extrusion speeds, as provided by EXALCO, vary from 4m/sec up to 10m/sec, depending on the produced extrusion profile. Average energy and gas consumption of the extrusion units used for aluminium extrusion is 0.24kWh/kg and 0.027m^3/kg respectively.

Another meaningful factor in a forming operation is the exact determination of the pressure (die profile optimization etc).

It is difficult, by means of analytic models, to determine the force of extrusion process exactly. Therefore, stochastic models especially provide wider possibilities in the solving of extrusion force. When the parameters of process became better-understood, extrusion force by means of stochastic modeling can be determined.

6.5 LASER MACHINING

Advantages/Disadvantages

The main advantages of Laser Machining are listed below:

- Flexible production “tools”
- Ideal to process materials that are difficult to process with mechanical processing (e.g. ceramics, composites, hardened alloys)
- Localized heat sources providing narrow Heat Affected Zones (HAZ),
- Very accurate and high speed processing
- Capability of processing a wide variety of part geometries and sizes, while achieving reasonable material processing rates.

The main laser disadvantage is the low energy efficiency of the process, since in order for the material to be removed by melting or vaporization relative high energy input is required [41].

Environmental aspects:

The system elements to be considered for an environmental analysis are:

4) *Laser source*: Its efficiency is quite low, strongly depending on the source typology. Typical overall efficiencies are from 6-8% for a CO_2 source, and up to 30% for a fiber source.
5) *Cooling system:* Given the high dissipated power in the laser source, the thermal efficiency of the cooling system can have a significant impact on the overall machine energy use.

In general fiber lasers easily outperform CO_2 lasers in terms of energy efficiency. Other advantages of fibre lasers:

5) *Cooling:* The efficiency of the fiber laser also contributes to lower cooling requirements, which contributes to lower electrical usage.

6) *Consumables/Replacement Parts and maintenance:* Because of the highly efficient design of fiber lasers (better thermal management) less replacement parts and maintenance are required. In all solid-state fiber-to-fiber lasers there are no optics to adjust or maintain, such as resonators mirrors, crystals, fluids and filters, as in conventional lasers.
7) *Capital costs:* With fiber lasers, the same laser can cut, weld and drill, lowering the investment costs.

It must be noted that in general laser process parameters are correlated each other and it is difficult to understand how the parameters have an impact on laser energy efficiency and on global energy consumption.

Trends and future developments

The future of the laser will be due to the improvement of:

- the comparison with other processes
- the monitoring of several parameters such as:
    - power consumption
    - material utilization rate

in order to ensure:

- costs reduction
- low maintenance
- safety systems
- production control
- quality increase
- productivity increase
- flexible production, able to adapt to market fluctuation
- high energy efficiency

Energy use by peripheral equipment such as cooling units and axes might be significant. Apart from the energy consumption directly related to the laser source, developments proposed by machines manufactures will generate further reduction in energy consumption, via:

- machines with higher dynamics and accuracy that allow a cycle time reduction while preserving the required machining accuracy
- axes equipped by linear motors and a rigid structure, reaching a combined speed up to 240 m/min
- machine architectures with redundant axes to involve small inertias in small motions with high acceleration
- laser head with a highly dynamic focus axis to preserve an optimal beam focusing during fast motion
- For large production batches, more complete and faster automation solutions are recently offered (e.g. adjusting the pallet transfer speed according to sheet weight), increasing productivity and, consequently, specific energy consumption.
- Numerical Controls with a higher computational power and new advanced algorithms for predictive trajectory control and axes management, permitting a significant cycle time reduction

6.6 EDM

Current WEDM research is focussed on the machining performance measures, process parameters and the design and manufacture of electrodes aimed at improving the material removal rate and surface finish

Eco-friendliness

Most of the efforts in past decades have been to increase machining speed without reducing the machining accuracy. However, these approaches have not considered the impact of cutting conditions on the consumption of energy and wire, which are important for both economic as well as ecological points of view.

Energy consumption & efficiency

It was found that a significant part of energy consumption was due to the water-cooling, spark generator and water injection systems. The obtained results show that by changing the cutting conditions higher energy efficiency may be obtained.

The power consumption value of injection pump and spark generation unit depends upon the process, while other components (filling pump, filter pump, auxiliary pump & cooler) are not affected by the process requirements.

- *Filling pump:* Only in use when filling the dielectric into the work tank.
    - PFilling = 1.62 kW
- *Filtration pump:* Forces the dielectric through the filters from the polluted tank to the clean tank.
    - Filtration = 0.81 kW
- *Auxiliary pump:* Supplies the ancillary functions (threading jets, cleaning, wetting of wire contacts).
    - PAuxiliary = 0.81 kW
- *Injection pump:* generates the pressure for the high-pressure injection.
    - PInjection = 0 ... 2.43 kW (depends on injection pressure)

Generator power depends on used technology for the machining. Moreover, generator power and cutting speed are functions of discharge frequency. Therefore, PGenerator = 0 ... 2.37 kW

6.7 WATER JET

Eco-friendliness

The environmental issues relevant to AWJM are listed below:

- *Water Use:* In some cases, water treatment may be necessary prior to draining. However, when machining hazardous materials, a "closed loop" system that recycles the water may be required.
- *Abrasive Use:* The spent abrasive and waste material is suitable for landfill. Environmental issues and concerns have led the researchers to use such mediums and abrasives that do not require disposal, recycling or lead to pollution.
- *Energy Consumption:* The pumps use a considerable amount of electricity.

Energy consumption & efficiency

With the exception of the computer console, there are no components that are constantly running regardless of whether or not a part is being produced. A case study was carried out and the results on the energy consumption are given below:

- *Computer Console:* The computer draws a constant 2A at 110 V, for any amount of time that the machine is on. $P_{comp}=0.22kW$

- *Motors:* There is no significant energy profile as a function of speed for the motors, and the existence of one would provide negligible values compared to the pump energy consumption.
- *Pump:* Contributes most of the overall power consumption during cutting. $P_{pump}=12kW$.

6.8 HANDING EQUIPMENT

Handling in modern day factories is mostly done with robots equipped with the appropriate grippers. Robots may increase the overall efficiency of a manufacturing plant by eliminating or minimizing lighting and heating levels needed to provide a suitable environment for factory floor staff. (Savings up to 8% per degree C reduction in heating levels, up to 20% by turning off unnecessary lighting). Because of the high degree of automatization and cyclically reparative behavior of robots, even little improvements in the efficiency of their systems may result in significant energy and CO_2 emission reduction in whole production. A further increase in efficiency can be achieved by installing multipurpose robots, with the ability to perform multiple functions on the production line and complete a job in as little as half the time.

Robotic Grippers

Grippers are a significant element of a handling robot and the energy they consume cannot be neglected. Flexible grippers come in four categories:

- *Vacuum Grippers*.
- *Pneumatic Grippers*.
- *Hydraulic Grippers*.
- *Servo-Electric Grippers.*

An important consideration when designing for efficiency should be the weight and size of the EOT itself. Having a small, light weight EOT impacts the size and the complexity of the robot. Smaller and lighter robots save energy through down-sizing.

Energy Efficiency increase of robots

Additional energy savings can be sought into:

- Appropriate selection of robot size.
- Shutting down robots during their production-free time.
- Buffering recuperated energy from braking in the capacitors of a DC-Bus, to use again during acceleration.
- Optimizing movement profile.
- Using asynchronous braking and brake power adjustment.
- Shut down robots and peripherals when not working.

Combining all the described strategic usage approaches like appropriate robot choice, robot shutdown, stand-by mode active usage, trajectory optimization methods, the technical advancements like asynchronous brake management, brake power adjustment, more reusing the recuperated energy, the total energy savings can exceed 40%.

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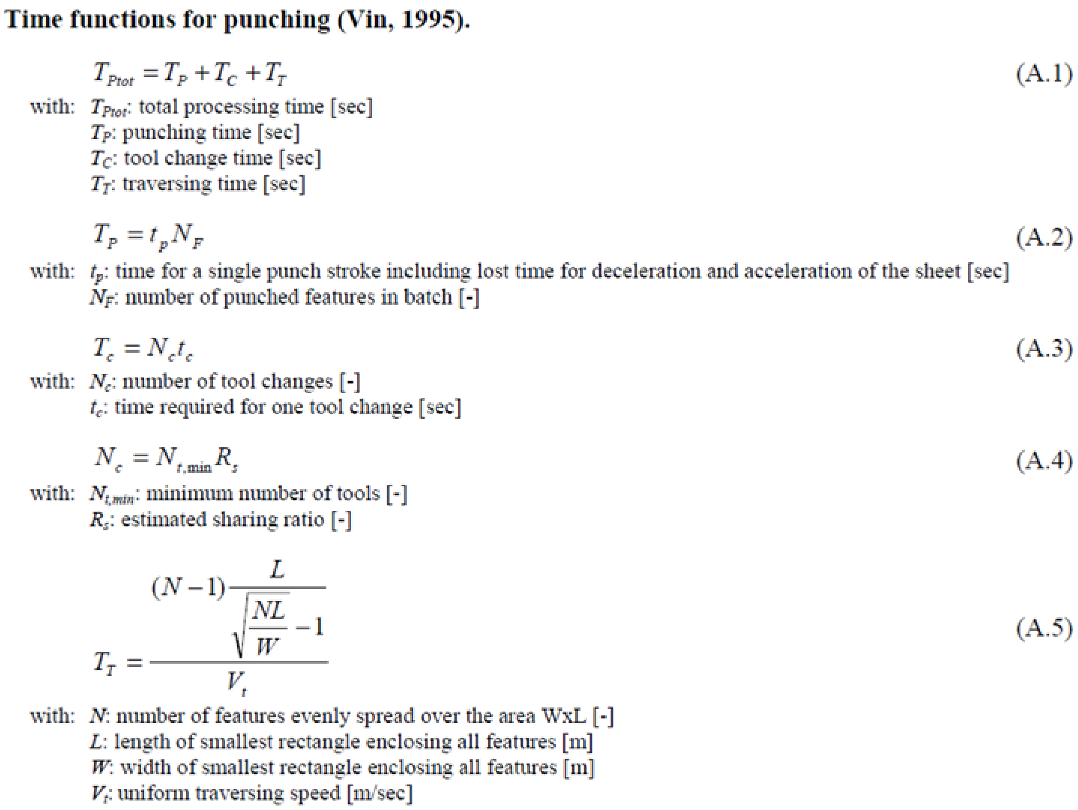
8 APPENDIX

8.1 APPENDIX 1- PUNCHING



Time functions for punching (Vin, 1995).

$$T_{Ptot} = T_P + T_C + T_T \tag{A.1}$$

with: T_{Ptot}: total processing time [sec]
T_P: punching time [sec]
T_C: tool change time [sec]
T_T: traversing time [sec]

$$T_P = t_p N_F \tag{A.2}$$

with: t_p: time for a single punch stroke including lost time for deceleration and acceleration of the sheet [sec]
N_F: number of punched features in batch [-]

$$T_c = N_c t_c \tag{A.3}$$

with: N_c: number of tool changes [-]
t_c: time required for one tool change [sec]

$$N_c = N_{t,\min} R_s \tag{A.4}$$

with: $N_{t,min}$: minimum number of tools [-]
R_s: estimated sharing ratio [-]

$$T_T = \frac{(N-1)\dfrac{L}{\sqrt{\dfrac{NL}{W}}-1}}{V_t} \tag{A.5}$$

with: N: number of features evenly spread over the area WxL [-]
L: length of smallest rectangle enclosing all features [m]
W: width of smallest rectangle enclosing all features [m]
V_t: uniform traversing speed [m/sec]

8.2 APPENDIX 2-NIBBLING

Time functions for nibbling (Vin, 1995).

$$T_{Ptot} = T_N + T_C + T_T \tag{A.6}$$

with: T_{Ptot}: total processing time [sec]
T_N: nibbling time [sec]
T_C: tool change time [sec]
T_T: traversing time [sec]

$$T_N = \sum_{i=1}^{N_N} (T_H(p) N_H)_i \tag{A.7}$$

with: N_N: number of nibbled features in batch [-]
$T_H(p)$: time for a single hit (function of pitch p) [sec]
N_H: number of hits required to make feature i [-]
i: feature i which has to be nibbled [-]

Time functions for nibbling (Nollet, 1993).

$$T_{tot} = T_s + T_w \tag{A.8}$$

$$T_s = \frac{t_{vs} + t_{gl} N_{tool}}{N_{tot}} \tag{A.9}$$

$$T_w = 1.05\left(t_{p1} + t_{p2} + t_{p3} + t_{p4} + t_{p5} + t_{p6} + t_{p7}\right) \tag{A.10}$$

$$t_{p1} = \frac{t_{epl}}{N_s} \tag{A.11}$$

$$t_{p2} = \left(N_{p1} + N_{p2}\right)\frac{a_{gem}}{v_{pos}} + t_{kap} \tag{A.12}$$

$$t_{p3} = \frac{L_{CT}}{L_T}\left(\frac{L_T}{v_{pos}} + t_{kap}\right) + \frac{a_{gem}}{v_{pos}} \tag{A.13}$$

$$t_{p4} = t_{nib} N_{nib} \tag{A.14}$$

$$t_{p5} = \frac{\left(N_{tool} - 1\right) t_{tw}}{N_s} \tag{A.15}$$

$$t_{p6} = \frac{t_{iu}}{N_s} \tag{A.16}$$

$$t_{p7} = \frac{t_{af}}{N_s} \tag{A.17}$$

with: T_{tot}: total processing time per workpiece [min]
T_s: set-up time for N_{tot} [min]
T_w: processing time per workpiece [min]
t_{p1}: time for startposition [min]
t_{p2}: effective punching time [min]
t_{p3}: nibbling time of rectangular contours [min]
t_{p4}: nibbling time of curved contours [min]
t_{p5}: time for removing scrap [min]
t_{p6}: fixing and unfixing time [min]
t_{p7}: time for removing scrap [min]
t_{vs}: fixed set-up time [min]
t_{gl}: time for one tool setup [min]
N_{tool}: number of different tools [-]
N_{tot}: total number of workpieces [-]
t_{epl}: time to move from zero to first cut [min]
N_s: number of parts per sheet [-]
N_{p1}: number of punches [-]
N_{p2}: number of punches to complete a contour [-]
a_{gem}: average distance between holes [mm]
v_{pos}: positioning speed [mm/min]
t_{kap}: time to for one punch [min]
L_{CT}: length of the rectangular contours [mm]
L_T: efficient length of the rectangular contours [mm]
v_{laser}: laser cutting speed [mm/min]
t_{nib}: time of a punch for curved contours [min]
N_{nib}: number of punches for curved contours [-]
t_{tw}: tool change time [min]
t_{iu}: time for fixing and unfixing a sheet [min]
t_{af}: time for removing scrap per sheet [min]

Cost functions for nibbling (Nollet, 1993).

$$K_{tot} = \left(K'_{vast} + K'_{\mathrm{var}}\right) T_{tot} + K_{tech} \tag{A.18}$$

$$K'_{vast} = \frac{1}{60}\frac{1}{hy}\left(\frac{PV}{PV_a} + R_{opp} O\right) \tag{A.19}$$

$$K'_{\mathrm{var}} = eu \cdot pe + k'_w + k'_m + k'_p \tag{A.20}$$

$$K_{tech} = N_p K_{1p} + N_t K_{1t} + N_{nib} K_{1nib} \tag{A.21}$$

$$N_p = N_{p1} + N_{p2} \tag{A.22}$$

with: K_{tot}: total costs per workpiece [costs]
K'_{vast}: fixed cost rate [costs/min]
K'_{var}: variable cost rate [costs/min]
T_{tot}: total processing time per workpiece [min]
K_{tech}: technology dependent costs [costs]
hy: working hours per year [hour]
PV: present value [costs]
PV_a: annuity factor [-]
R_{opp}: costs of surface area [costs/m^2]
O: area [m^2]
eu: electricity usage [kWh]
pe: price of electricity [costs/kWh]
k'_w: labour rate [costs/min]
k'_m: maintenance rate [costs/min]
k'_p: programming rate [costs/min]
N_p: total number of punches [-]
K_{1p}: tool costs of one punch [costs]
N_t: number of punches for rectangular contours [-]
K_{1t}: tool costs of one punch in rectangular contour [costs]
N_{nib}: number of punches for curved controus [-]
K_{1nib}: tool costs of one punch in curved contour [costs]
N_{p1}: holes in the workpiece [-]
N_{p2}: punches from the contours [-]

8.3 APPENDIX 3-CUTTING

Time functions for cutting (Cuesta, 1998).

$$T_{batch} = T_{pre} + T_c + T_{aux} + T_{pro} \tag{A.23}$$

with: T_{batch}: production time for a batch [min]
T_{pre}: preperation time [min]
T_c: cutting time [min]
T_{aux}: auxiliary time [min]
T_{pro}: programming time [min]

$$T_{pre} = \sum_{j=1}^{m}(T_{NC1} + T_{NC2} + T_{NC3})_j + \sum_{k=1}^{p}(T_{SH1} + T_{SH2} + T_{SH3})_k + \sum_{l=1}^{q}(T_{Tool})_l + \sum_{n=1}^{r}(T_{Sp})_n \tag{A.24}$$

with: m: number of NC programmes used per machine [-]
p: number of sheets present in the batch [-]
q: number of tools loaded per machine [-]
r: number of specimens to make [-]
T_{NC1}: loading and selection time for NC program j [min]
T_{NC2}: time required for tool position (returns and set tool to the program origin) [min]
T_{NC3}: program start-up time [min]
T_{SH1}: time for loading sheet/part k [min]
T_{SH2}: time required for tool (e.g. positioning) and sheet/part preparation for sheet k (previous heat treatment, etc.) [min]
T_{SH3}: time unloading or changing sheet/part k [min]
T_{Tool}: time loading tool l [min]
T_{Sp}: time to produce one specimen (e.g. bending) [min]

$$T_c = \sum_{i=1}^{n}(T_{ci} + T_{nci}) \qquad P_c = \sum_{i=1}^{n} N_i (P_{ci} + P_{nci}) \tag{A.25}$$

with: n: the numberof time-files (number of NC programs) [-]
T_c: effective cutting time (for all the NC programs) [min]
P_c: effective cutting perimeter (for all the NC progams) [m]
T_{ci}: cutting time for the *i*th program [min]
T_{nci}: rapid (noncutting) time for the *i*th program[min]
P_{ci}: cutting perimeter for the *i*th program [m]
P_{nci}: rapid (noncutting) perimeters for the *i*th program [m]
N_i: number of simultaneous tools for the ith program (N_i = 1,2,4,6,...,12) [-]

Cost functions for cutting (Cuesta,1998).

$$C_{batch} = C_{mt} + C_{mat} + C_t + C_{pro} \tag{A.26}$$

with: C_{batch}: total costs per batch [costs]
C_{mt}: machine-tool costs [costs]
C_{mat}: material costs [costs]
C_t: tooling costs [costs]
C_{pro}: programming costs [costs]

$$C_{mt} = x\frac{T_{batch}}{60} \tag{A.27}$$

$$x = C_{ms} + C_{ml} + C_{ma} + C_{mp} + C_{mt} + C_{mi} \tag{A.28}$$

$$C_{ms} = N_{ft} P_s \tag{A.29}$$

$$C_{ml} = \frac{S_t P_{re}}{H_{mt}} \tag{A.30}$$

$$C_{ma} = \frac{P_{mt}}{T_a H_{mt}} \tag{A.31}$$

$$C_{mp} = P_{kw} E_{mt} \frac{r}{100} \tag{A.32}$$

$$C_{mt} = \frac{K}{100}\frac{P_{mt}}{H_{mt}} \tag{A.33}$$

$$C_{mi} = \frac{C_{ind}}{H_{mt}} \tag{A.34}$$

....

with: C_{ms}: labour expenditure or operator income cost rate [costs/hour]
C_{ml}: machine-location cost rate, lighting, etc. [costs/hour]
C_{ma}: machine-tool amortisation cost rate [costs/hour]
C_{mp}: electrical power consumption [costs/hour]
C_{mt}: maintenance and reparations cost rate [costs/hour]
C_{mi}: machine-tool indirect costs rate [costs/hour]
N_{ft}: number of full-time operators per machine-tool (usually $N_{ft} = 1$) [-]
P_s: labour cost rate [costs/hour]
P_{mt}: total machine-tool price [costs]
T_a: amortisation time or period [years]
H_{mt}: working machine-tool hours per year [hour/year]
S_t: total working area, including operator and machine-tool areas [m^2]
P_{re}: price of shop floor rent, lighting, etc. [costs/m^2-year]
K : maintenance and reparation supplement (usually $K \approx 3\%$ of the total machine-tool price)
P_{kw}: kWh price [costs]
E_{mt}: machine-tool power [kW]
r: machine utilisation rate (%)
C_{ind}: indirect and annual cost which could be charged to the machine-tool [costs/year]

$$C_{mat} = \sum_{j=1}^{m} n_j \left\{ \left(1 + \frac{K_a}{100} \right) \left[10^{-3} w_j \rho_j Sb_j \right] P_{sh} - \left[10^{-3} w_j \rho_j Sr_j \right] P_j \right\} \tag{A.35}$$

with: m: number of equal sheets and equal cutting way (the same areas and the same cutting perimeters) [-]
n_j: number of equal sheets (like the jth sheet) and equal cutting way (the same areas and the same cutting perimeters) [-]
K_a: generic supplement for loading, internal transport, etc [%]
w_j: jth sheet thickness [mm]
ρ_j: jth sheet density [kg/m^3]
Sb_j: original jth sheet area [m^2]
P_{sh}: original sheet price [kost/kg]
Sr_j: remaining jth sheet area [m^2]
P_j: remaining material price in the jth sheet: $P_j = P_{sh}$ when the remaining material (Sr_j) is for offcut re-use and $P_j = P_{sc}$ when (Sr_j) is sold like scrap [costs/kg]
S_{sc}: material metal scrap sale price [costs/kg]

$$C_t = C_{gas1} + C_{gas2} + C_{tor} + C_{tk} + C_{bot} \tag{A.36}$$

$$C_{gas1} = 10^{-3} C_{g1} P_{g1} P_c \tag{A.37}$$

$$C_{gas2} = 10^{-3} C_{g2} P_{g2} P_c \tag{A.38}$$

$$C_{tor} = \frac{P_{tor}}{H_s} \frac{T_c}{60} \tag{A.39}$$

$$C_{tk} = P_{tk} \frac{T_{batch}}{43200} \tag{A.40}$$

$$C_{bot} = (N_b P_{bot} + P_{bt} C_b) \frac{T_{batch}}{43200} \tag{A.41}$$

with: C_{gas1}/C_{gas2}: gas 1 and gas 2 consumption [litre/m]
P_{g1}/P_{g2}: gas 1 and gas 2 price [costs/m^3]
P_c : effective cutting perimeter [m]
T_c : effective processing time [min]
T_{batch}: production time [min/lot]
N_b: number of rented bottles [-]
P_{tk}: price for tank-rent [costs/month]
P_{bot}: price for bottle-rent [costs/month]
C_b: bottles consumption [bottles/month]
P_{bt}: bottles transport price [costs/bottle]
P_{tor}: tool price (torch, gauges, and all devices) [costs]
H_s: average tool life estimate [hour]
C_{bot}: total bottle cost [costs]
C_{tk}: total tank cost [costs]
C_{tor}: total tool cost [costs]

$$C_{pro} = P_{pro} \frac{T_{pro}}{60} \tag{A.42}$$

with: P_{pro}: programmer cost rate [costs/hour]
T_{pro}: programmer cost rate [costs/hour]

8.4 APPENDIX 4-BENDING

Time function for bending (Somatech, 1998).

$$T_{Ptot} = \sum_{i=1}^{N_p} \left(n_s \left(n_{ab} T_{ab} + n_{shp} T_{shp} + n_{tx} T_{tx} + n_{ty} T_{ty} + n_{tz} T_{tz}\right)\right)_i \qquad \text{(A.60)}$$

with: T_{ptot}: production time for a batch [sec]
N_p: number of products in batch [-]
n_s: skill factor for worker (≥1) [-]
n_{ab}: number of bends [-]
n_{shp}: number of shove movements [-]
n_{tx}: number of x turnings [-]
n_{ty}: number of y turnings [-]
n_{tz}: number of z-turnings [-]
T_{ab}: time to produce a single bend [sec]
T_{shp}: time to shove the part [sec]
T_{tx}: time to turn the part in the x-plane [sec]
T_{ty}: time to turn the part in the y-plane [sec]
T_{tz}: time to turn the part in the z-plane [sec]

Time functions for bending (Maree, 1997).

$$T = s + ((m * p) * b) * rp \qquad \text{(A.61)}$$

with: T: time to complete the process [sec]
s: set-up time = 45 for 90° bends, 105 for other angles [sec]
m: measuring correct dimensions and marking it on the part = 20 [sec]
p: process time = 8 for 90° bends, 16 for other angles [sec]
b: number of bends per part [-]
rp: repeats [-]

$$T = s + \left(m + \frac{A * ct * Ang}{90}\right) * rp \qquad \text{(A.62)}$$

with: T: time to complete the process [sec]
s: set-up time = 20 [sec]
m: measuring correct dimensions and marking it on the part = 15 [sec]
A: cross-section area of the part [mm^2]
ct: time factor for the process = 0.5 [-]
Ang: angel to be bent [degrees]
rp: repeats [-]