Modelling and simulation of a manufacturing process, approaches and examples

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1. Introduction

Nowadays the market fluctuation and the fashion ask for more and more new and different patterns, the batch size decreases, it is necessary to design and manufacture with reducing delays. So the concept of concurrent engineering (Sohlenius 1992, Tichkiewitch S. and Véron M. 1997) must be used. The design of the parts, the production planning and the production system must be made quite simultaneously. So the design and development cycle is reduced and the manufacturing constraints are taken into account as soon as possible and the design phase must take into account of manufacturing constraints but these ones must not restrict designer creativeness.

Integration product-process concept is illustrated in figure 1: the quality of mechanical parts depends on the expression of specifications (shapes, functions, dimensions, surface quality, and materials), the ability of shaping processes and resource capability (defects in machine-tools, tools, machinery). To meet optimisation objectives, models and processes are used to generate production processes or design production systems or to validate a product's productibility, as well as defining the product qualification procedure. By process, we mean manufacturing processes (forging, casting, stamping, machining, assembling, rapid prototyping..), production resources (machines, toolings..), and conditions for implementation (set-up, fixtures, operating conditions…), operation scheduling and the structure of the installation. Production constraints (process, capability, producible shapes, precision...) must be taken into account at the same time as economic (cost...), logistics (lead-times, reactivity, size of production runs...) or legislative (recycling, safety...) constraints. On the one hand, knowledge and constraints must be structured, formalized and represented (data and processes), using experimental data (processes and resources) and models of industrial conditions so that different types of expertise can be coherently integrated using appropriate models, methods and tools so as to meet production optimisation objectives (quality, reactivity, productivity, cost…).

Concurrent engineering is undertaken following several ways:

- how to get a new organisation between several services (design, marketing, production..) in order to reduce drastically the product development cycle,

- data exchanges between the several computer models used, information system structured, data management all along the life product cycle,

- knowledge integration: how to formalise and structure the knowledge (data and processing) taking into account of the constraints (technical, manufacturing, logistics, cost..) simultaneously when it is necessary during the design phase. Specific criteria (coherence, constancy, accuracy, robustness, tracability…) have to be added in order to allow the constancy and the robustness of the model. .

The two first points are already implemented in industry (organisation by project, project platform…), normalized exchanges standard (CALS, STEP) between CAD softwares or work on the same virtual model and are also the theme of academic works (Vernadat 1996, Bernard A.and Perry N. 2002, Feng S. and Song E. 2000, Roucoules L.and Skander A. 2004). We will focus on the last point and will give an illustration of this wide problem for manufacturing process planning.
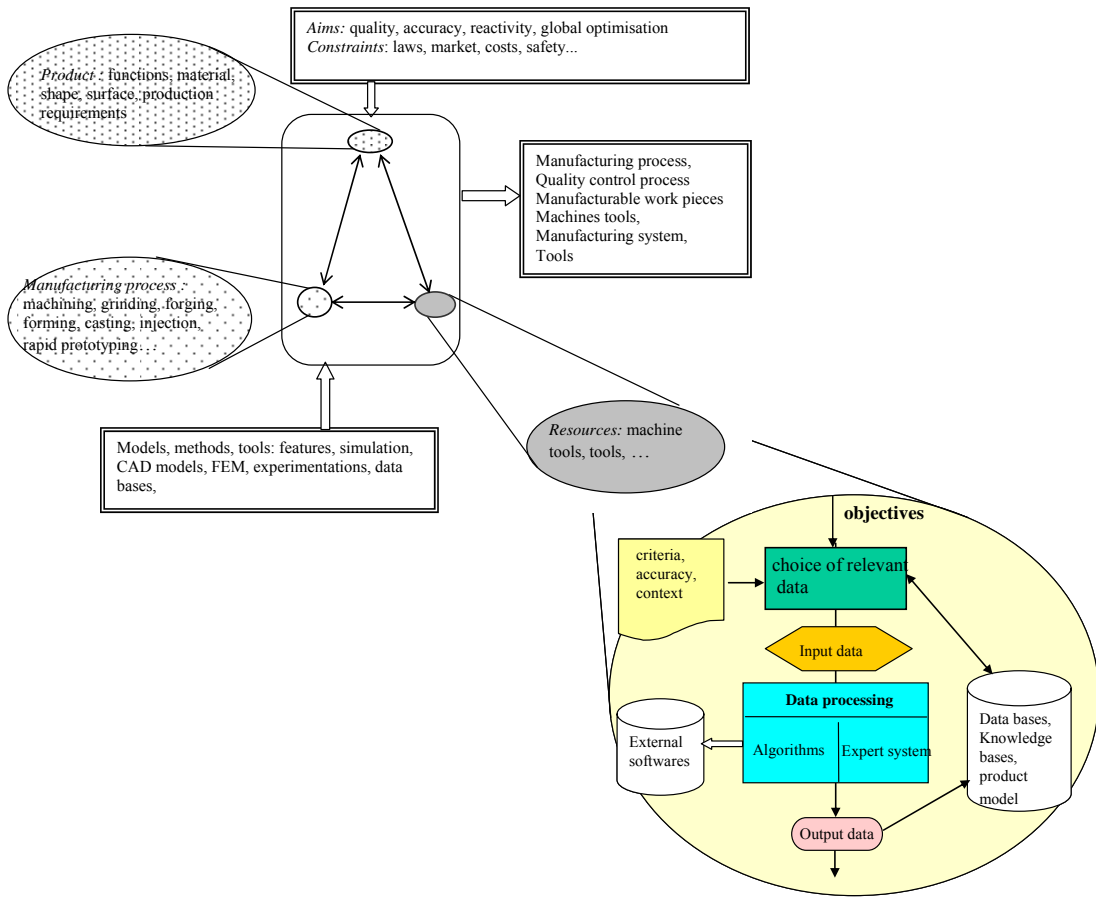
Fig. 1. : Reference diagram of our approach (Martin 2005)

2.   Process planning

Process planning translates design information into the process steps and instructions to efficiently and effectively manufacture products. Process planning encompasses the activities and functions to prepare a detailed set of plans and instructions to produce a part. The planning begins with engineering drawings, specifications, parts or material lists and a forecast of demand.

The results of the planning are:

-   routings which specify material process, operations, operation sequences, work centers, standards, tooling and fixtures. This routing becomes a major input to the manufacturing resource planning system to define operations for production activity control purposes and define required resources for capacity requirements planning purposes.

-   process plans which typically provide more detailed, step-by-step work instructions including dimensions related to individual operations, machining parameters, set-up instructions, and quality assurance checkpoints.

-   fabrication and assembly drawings to support manufacture (as opposed to engineering drawings to define the part).

Manual process planning is based on a manufacturing engineer's experience and knowledge of production facilities, equipment, their capabilities, processes, and tooling. Process planning is very time-consuming and the results vary based on the person doing the planning. As the design process is supported by many computer-aided tools, research on computer-aided process planning (CAPP) has been undertaken since 1990 (Halevi G. and Weill R.1995, El Maraghy H.A. 1993, Brissaud D. and Martin P. 1998) but it stay to a low degree of automatisation (figure 2) because it stay very difficult to formalize expert knowledge, a lot of solutions are acceptable, the context (part shape and accuracy, batch size, material, cost..) introduce constraints which have important influence on the process planning choice. More works has been developed in the frame of machining process, in this paper we will interest to primary and secondary process (figure 3).

The objective of this paper is to illustrated the approach we proposed to determine the process planning, it is based of an example coming from automotive industry, the purpose is to find

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several manufacturing processes in order to compare them by taking into account of technical, logistical and economical constraints, we have to choose different processes that are convenient for the product.
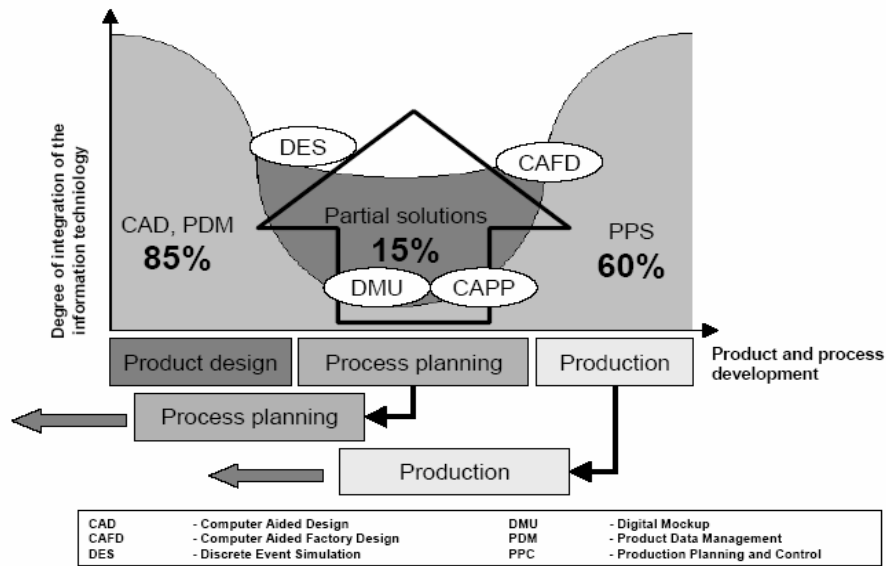

Fig. 2. : Development of integration in the development process (Zaeh M. F. and al. 2005)
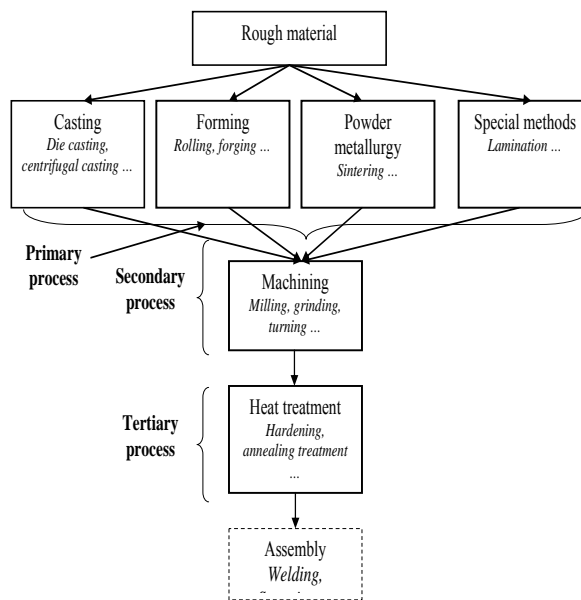

Figure 3 - General manufacturing processus (Ashby M.F,, Michael F. 2004)

Prior to CAPP, manufacturers attempted to overcome the problems of manual process planning by basic classification of parts into families and developing somewhat standardized process plans for parts families. When a new part was introduced, the process plan for that family would be manually retrieved, marked-up and retyped. While this improved productivity, it did not improve the quality of the planning of processes and it did not easily take into account the differences between parts in a family nor improvements in production processes.

This initial computer-aided approach evolved into what is now known as "variant" CAPP. However, variant CAPP is based on a Group Technology (GT) coding and classification approach to identify a larger number of part attributes or parameters. These attributes allow the system to select a baseline process plan for the part family and accomplish about ninety percent of the planning work. The planner will add the remaining ten percent of the effort modifying or fine-tuning the process plan. The baseline process plans stored in the computer are manually entered using a super planner concept, that is, developing standardized plans based on the accumulated experience and knowledge of multiple planners and manufacturing engineers.

The next stage of evolution is toward generative CAPP. At this stage, process planning decision rules are built into the system. These decision rules will operate based on manufacturing features for describing the part and algorithms or expert systems for computing. A further step in this stage is dynamic, generative CAPP which would consider plant and machine capacities, tooling availability, machining centre and equipment loads, and equipment status (e.g., maintenance downtime) in developing process plans.

Numerous ways have been tested and it is not the matter to be exhaustive here: let you see El Maraghy 1993, Leung H.C. 1996, Salomons and al.1993, Shah J.J.and al. 1994,

CAPP benefits

Significant benefits can result from the implementation of CAPP. In a detailed survey of twenty-two large and small companies using generative-type CAPP systems, the following estimated cost savings were achieved:

- 58% reduction in process planning effort
- 10% saving in direct labor
- 4% saving in material
- 10% saving in scrap
- 12% saving in tooling
- 6% reduction in work-in-process

In addition, there are intangible benefits as follows:

- Reduced process planning and production leadtime; faster response to engineering changes
- Greater process plan consistency; access to up-to-date information in a central database
- Improved cost estimating procedures and fewer calculation errors
- More complete and detailed process plans
- Improved production scheduling and capacity utilization
- Improved ability to introduce new manufacturing technology and rapidly update process plans to utilize the improved technology.

3. Casting process

Casting aims at producing mechanical parts by filling a stamp with a melting metallic alloy. Casting is an important phase of the manufacturing process. Not only it gives us the rough geometry of the product but it also determines the machining operations that we should do in order to satisfy the customer's requirements.

Casting process can be described by the following steps:

- Elaboration of the metallic alloy. Some chemical elements may be added to the melting metallic alloy to improve the mechanical properties of the material.
- Design of the mold. This mold may be permanent or non-permanent. To be built it requires a model of the part to cast. These models are generally in wood or in wax.
- Perfection. During this step all the feeders, the systems of filling have to be cut. The burrs resulting from the gap between the different parts of the mold are ground down.
- Control of the part.
- Heat treatment in order to improve the physical properties of the part.

In order to define the processes and the materials that are the most convenient for manufacturing a part, we used the software CES edupack 2006 that is based on Ashby method (Ashby M.F and Michael F. 2004).

By using Ashby method, we listed all the processes known and then we imposed constraints to reduce the number of processes to 3 in our example. Table 1 summarizes the performance index that we have retained.

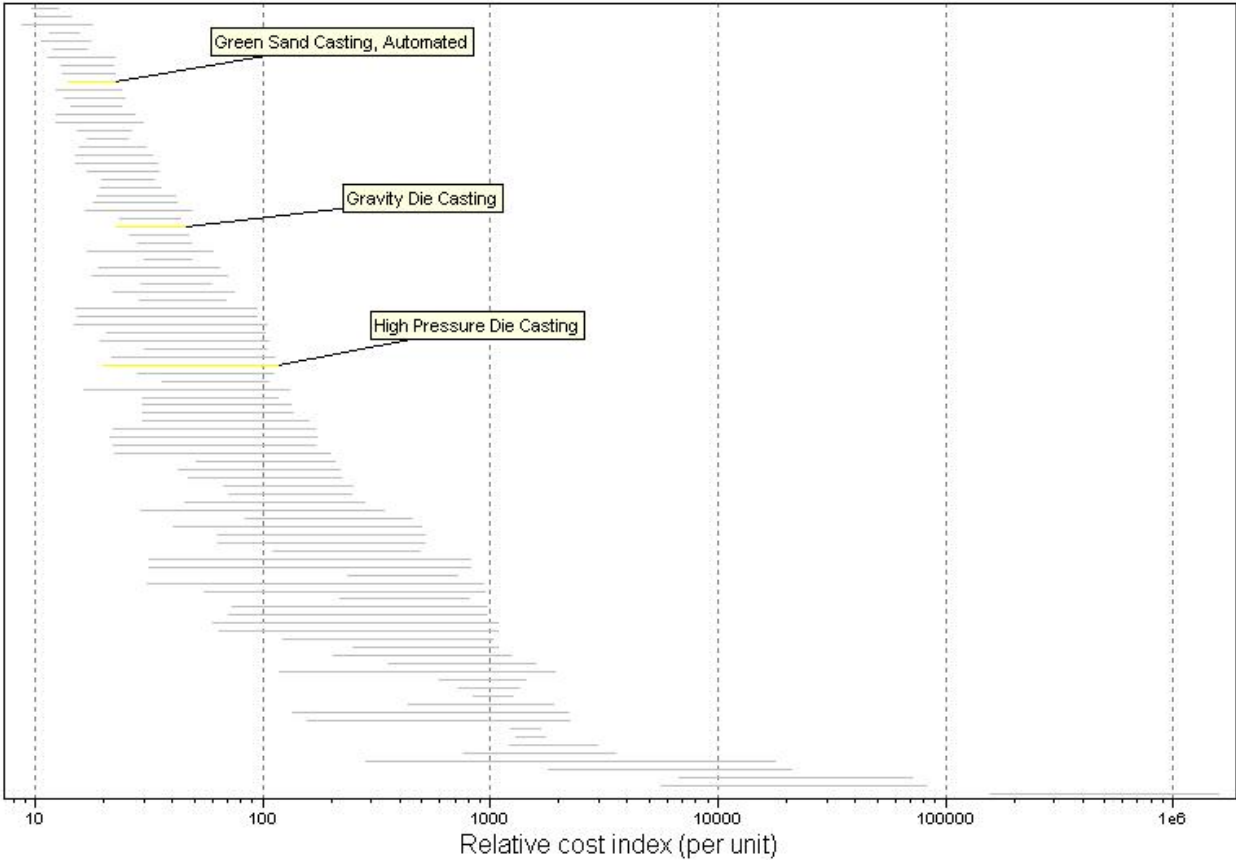| Constraint	Value	Number of processes corresponding
	All processes	135
Process	Casting processes	21
Production rate	>175 kg/h	10
Tool life	>100,000 cycles	3

Table 1: constraints table for Ashby method

In this study we only considered casting processes. Indeed casting is the cheapest and the most common way to produce the rough geometry of the part. We fixed a production rate because the pump block is produced in big series. Figure 4 shows the selected processes. The processes that we have selected by using the Ashby method are green sand casting, gravity die casting and high pressure die casting.

At this point we have selected 3 processes. Now we have to select materials that correspond to these processes. For that we have used the same method as previously like it is shown in table2.

The constraints we have fixed give us a choice between 8 materials but several materials in this list may be dropped. This is the case of aluminum alloy for forging (2 kinds of alloy, thermosetting one and not thermosetting one), magnesium alloy for forging, zinc alloy for injection. Moreover among the remaining materials, there are 2 kinds of cast iron so we can choose one of these 2 kinds.

Therefore the 3 selected materials are aluminum alloy for casting, magnesium alloy for casting and cast iron.

Now we have a list of processes and a list of materials. We must combine these lists to purpose several manufacturing scenarios. Table 3 shows the processes we will simulate for each material.

Figure 4: selected processes

Constraint	Value	Number of materials corresponding
	All materials	94
Price	<3 €/kg	58
Yield point	>125 MPa	17
Melting ability	>4 over 5	11
Volumetric mass	<7100 kg/m^3	8

Table 2 : constraints for material choice

Process number	Material	Kind of mold	Kind of process
1	Al-Si 9 Cu 3	Permanent	Gravity casting
2	Al-Si 9 Cu 3	Permanent	Die casting
3	Al-Si 9 Cu 3	Non-permanent	Green sand
4	FGL-250	Non-permanent	Green sand
5	AM50	Permanent	Die casting

Table 3: description of the processes simulated

Properties obtained with the different processes

The shrinking effect does not happen the same way for different kinds of alloy. As it is shown in the table 4 below, the shrinking is more significant for aluminum alloy than for cast iron.

Alloy	Liquid shrinking	Solid shrinking
Al-Si	3.5 to 5 %	1.1 to 1.3 %
FGL	0.5 to 3 %	0.5 to 1.2 %
AM50	4%	5%

Table 4: shrinking as function of alloy

The roughness and the dimensional accuracy depend not only on the choice of alloy but also on the choice of process. Table 5 shows the roughness as function of alloy and of process. We can notice that roughness is better for die casting than for gravity casting and much better than for green sand. Moreover aluminum alloy roughness is more likely to be low than cast iron roughness. Table 6 shows the dimensional accuracy in millimeter for a dimension equals to 200 mm.

Roughness (µm)	Aluminum alloy	Cast iron	Magnesium alloy
Gravity casting	1.6 to 6.3	n/a	2
Die casting	0.8 to 1.6	n/a	1.5
Green sand	6.3 to 12.5	6.3 to 25	10

Table 5: roughness as function of alloy and process

Dimensional accuracy (mm)	Aluminum alloy	Cast iron	Magnesium alloy
Gravity casting	+/- 0.8	n/a	+/- 0.8
Die casting	+/- 0.3	n/a	+/- 0.3
Green sand	+/- 1.5	+/- 2	+/- 0.8

Table 6: dimensional accuracy as function of alloy and process

Simulation of the processes

In order to estimate the time of solidification for each of the 5 processes studied, we have performed a simulation of these processes with the software Magmasoft 4.2, which is routinely used in casting industry. Even if this software is quite accurate, the results obtained are only approximations because we did not consider feeders or filling system, we just considered the part. The first step to do is to import the part under the right format. It can be easily done with the software CATIA (Dassault Systemes) by using the fast prototyping module.

Then we must create the project on Magma and specify the record folder. The next step is dedicated to the building of the mold. We must choose the type of the mold permanent or sand mold. It is directly obtained from the part. As it is shown on the following picture, we just have to input the external boundaries of the mold while the internal ones are virtually calculated by the software. Once the mold is built, we have to perform the enmeshment of the part. It is used by the software to calculate the material flow and the temperature inside the part. The user input the number of elements that will compose the enmeshment (figure 5). The more elements there are, the most accurate the results are, but the longer the simulation is. In our case, we divided the part in 4 000 000 elements, which may take 1 hour or more to simulate.
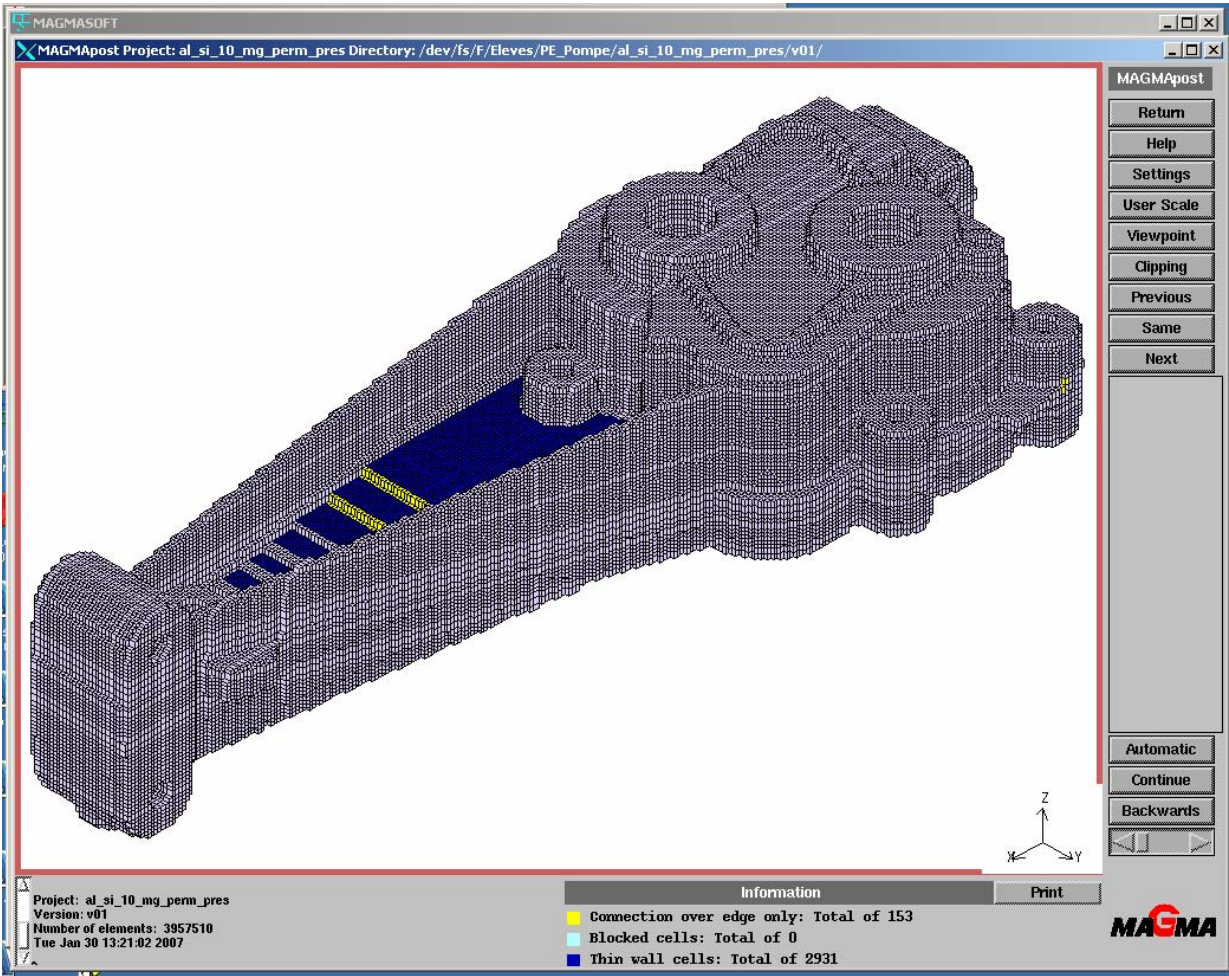

Figure 5: mold enmeshment with magma

The final step is to define the parameters of the simulation. First we specify the process, for instance green sand or die casting. We also configure the temperature of the mold. Generally it is equal to the temperature of the room for green mold and about 250°C for permanent mold.

Then we can choose material among a list purposed by the software. In the database of magma, each material is defined by its liquidus and solidus temperature, its volumetric mass, its latent heat and other parameters. When we select a material, we can also define the filling temperature. Practically the lower this temperature is, the cheaper the process is, but the product has more chance to be insane. In our study, we did not consider any change in temperature for the processes and we selected the default values (700°C for aluminum alloy and 1400°C for cast iron).

The following step is to input the heat transfer coefficient between the part and the mold. This coefficient is temperature depending, because of the shrinking of the part. There is a heat transfer coefficient different for each couple material/mold. We have the possibility to shake out the part or to perform a quenching. In our study we do not consider quenching. Finally we input the conditions of ending the simulation. We can choose to stop it after some time or when the maximal temperature of the part drops under a limit value.

Simulations

Process 1: Gravity Casting, aluminum alloy

     Alloy : Al Si 9 Cu 3 with initial temperature equals to 670°C

     Mold: steel with initial temperature equals to 250°C

     Heat transfer coefficient: temperature dependent (Al Si 9 Cu 3/mold)

     Opening parameter: temperature (400°C)

Process 2: Die casting, aluminum alloy (figure 6).

     Parameters defined:

     Alloy : Al Si 9 Cu 3 with initial temperature equals to 670°C

     Mold: steel with initial temperature equals to 250°C

     Heat transfer coefficient: temperature dependent (Al Si 9 Cu 3/HPDC)

     Opening parameter: temperature (400°C)
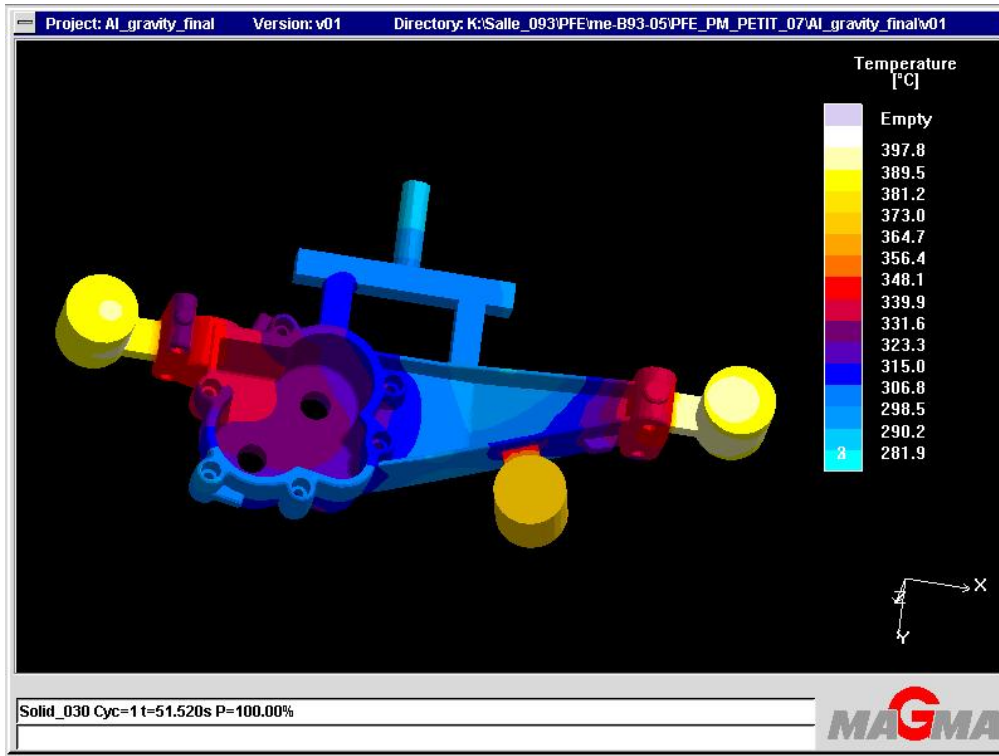
Process 3: Green Sand, aluminum alloy

Alloy : Al Si 9 Cu 3 with initial temperature equals to 670°C

Mold: green sand with initial temperature equals to 20°C

Heat transfer coefficient: temperature dependent (Al Si 9 Cu 3/sand)

Opening parameter: temperature (400°C)

Figure 6: temperature distribution at 400°C for process 2

The table 7 summarizes the results of the simulations.

Process	Time (s)
Gravity casting	40
Die casting- aluminum alloy	25
Green sand –aluminum alloy	234
Green sand- cast iron	1170
Die casting – magnesium alloy	13

Table 7: solidification times

We notice that the processes with permanent mold are faster than the processes with sand mold. Indeed steel has a better heat transfer coefficient than sand. To correct this difference, we may think about filling several parts in the same mold for green sand process. However this difference is not really a problem because in gravity and die casting the product solidifies inside the machine, we can not fill other products when a product is solidifying while with green sand processes we can fill other products when some products are solidifying.

Gravity casting takes more time than die casting. This is due to the feeders. Indeed the feeders are bigger for gravity casting than for die casting so they take more time to solidify. As die casting is quicker than gravity casting we expect to have a gain of production, but the tools are a little more expensive so we need to estimate more in details the cost of these processes.

In the same way, magnesium alloy appears to be more interesting than aluminum alloy because the casting time is divided by 2. Yet we have to check if the cost of the materials will compensate or not for this difference of production time.

Cost estimation for the different processes

Now the goal is be to detail the costs of production for each process studied.

Basically the cost of the processes depends on the following parameters: cost of material, cost of working force, cost of energy, and cost of machines. In order to estimate these costs, we have listed the different operations that compose the processes and for each operation we answered the following questions: what machine performs this operation? How many workers does it need? How much time does it need to perform the operation? How much energy does it consume?

For all the processes, the cost of 1 Wh is 0.0778 €. This is the price fixed by EDF, the company that produces and sells electricity. (Price fixed since august 2006).

The cost of working force is estimated to 25€ per hour. It includes the different governmental taxes and charges that the company must pay.

To build the model that will help us to estimate the cost of the processes, we have divided these processes in 5 steps. This division is the same for all the processes, but the steps may be performed differently according to the material or the process.

•	Alloy processing: the alloy is melt and then kept in the desired temperature.

•	Filing: the melt alloy is transferred from the furnace to the casting machine by a robot

•	Casting: the alloy solidifies inside the die

•	Burring: this operation consists in cutting all the unnecessary parts like feeders or filing system. It is done by a robot.

•	Control: this operation consists in checking the dimensions and the porosity of the product.

If the filing, burring and control steps are the same for all the processes, the cost of these steps may be different because the number of products performed with a process is different according to the process.

In the following tables the cost of each operation is represented. We divided the costs in 4 categories: material cost, working force cost, energy cost and machine cost. Machine costs were evaluated singly, based on a yearly production of 100,000 products and amortized on 6 years.

For each of the five identified processes we estimate the production cost shown in tables 8 to 12.

Costs per products	Alloy processing	Filing	Casting	Burring	Control	Total
Cost of material	3.72 €					3.72 €
Cost of working force	0.22 €		0.23 €	0.16 €	0.21 €	0.81 €
Cost of energy	0.09 €	0.003 €	0.009 €	0.003 €	0.003 €	0.10 €
Cost of machines	0.17 €	0.03 €	0.36 €	0.03 €	0.02 €	0.62 €

Table 8: cost estimation for process 1: gravity casting, aluminium alloy

Costs per products	Alloy processing	Filing	Casting	Burring	Control	Total
Cost of material	2.90 €					2.90 €
Cost of working force	0.14 €		0.14 €	0.16 €	0.21 €	0.64 €
Cost of energy	0.07 €	0.002 €	0.02 €	0.002 €	0.003 €	0.09 €

| Cost of machines | 0.17 € | 0.03 € | 0.64 € | 0.03 € | 0.02 € | 0.89 € |

Table 9: cost estimation for process 2: die casting , aluminium alloy

Costs per products	Alloy processing	Filing	Casting	Burring	Control	Total
Cost of material	4.08 €					4.08 €
Cost of working force	0.19 €		0.13 €	0.16 €	0.21 €	0.68 €
Cost of energy	0.10 €	0.002 €	0.01 €	0.002 €	0.003 €	0.11 €
Cost of machines	0.17 €	0.03 €	0.42 €	0.03 €	0.02 €	0.67 €

Table 10 : cost estimation for process 3, sand mold , aluminium alloy

Costs per products	Alloy processing	Filing	Casting	Burring	Control	Total
Cost of material	6.17 €					6.17 €
Cost of working force	0.02 €		0.13 €	0.16 €	0.21 €	0.63 €
Cost of energy	0.20 €	0.003 €	0.01 €	0.002 €	0.003 €	0.22 €
Cost of machines	0.32 €	0.03 €	0.42 €	0.03 €	0.02 €	0.83 €

Table 11 : cost estimation for process 4, sand mold , cast iron

Costs per products	Alloy processing	Filing	Casting	Burring	Control	Total
Cost of material	3.0 €					3.0 €
Cost of working force	0.09 €		0.10 €	0.16 €	0.21 €	0.55 €
Cost of energy	0.05 €	0.001 €	0.01 €	0.002 €	0.003 €	0.07 €
Cost of machines	0.16 €	0.03 €	0.74 €	0.03 €	0.02 €	0.98 €

Table 12 : cost estimation for process 5: die casting , titanium alloy

In order to estimate the robustness of the model, the cost of each process was calculated for different number of products done per year (table 13).

Number of products/year	1000	2000	5000	10000	20000	50000	100000	200000
Process1	46.5 €	25.67 €	13.17 €	9.0 €	6.92 €	5.67 €	5.25 €	5.04 €
Process2	62.28 €	33.11 €	15.61 €	9.78 €	6.86 €	5.11 €	4.53 €	4.24 €
Process3	76.49 €	40.66 €	19.16 €	11.99 €	8.41 €	6.26 €	5.54 €	5.18 €
Process4	95.31 €	51.14 €	24.64 €	15.81 €	11.39 €	8.74 €	7.86 €	7.42 €
Process5	70.59 €	37.26 €	17.26 €	10.59 €	7.26 €	5.26 €	4.59 €	4.26 €

Table 13 : process cost as function of number of products done

Conclusion

After having performed the simulation above, it appears that the best process is process 2: die casting with aluminum alloy. Its cost is estimated to 4.53€ per product.

Process 5 is interesting too, because not only its cost is near from process 1 cost, 4.59€, but it allows to reduce the weight of the part. Therefore if the price of magnesium decreases, this solution may be preferable to process 2.

Process 1 and process 3 are quite near from each other, respectively 5.25€ and 5.54€ but they are more expensive than die casting process, so these 2 solutions are not interesting for this product.

Finally process 4 is too much expensive to be interesting. Moreover it involves an increase of the weight of the product that does not correspond to the customer's needs.

The model that we created in this project is quite exact. Indeed we obtain a cost of 4.53€ per product for die casting process while the true process given by the manufacturer is 4.0€ per product. The difference is due to the fact that the depreciation of machines is compensated only by 1 product in our study while in a true company the depreciation is compensated by several products. Moreover the cost of the die is beard by the customer so we can deduce it from our estimation.

We can also affirm that our model is relatively reliable. Indeed when we modify the value of a parameter like the number of products performed per year, we notice that die casting process is the best process for series superior or equal to 20,000 products. However there is vulnerability in this model because for series inferior to 2,000 products, green sand process should be cheaper than the other one. It also may be explain by the fact that only 1 product bears the depreciation and for small series, depreciation is the most important part of cost. Finally, after having performed all these simulations, we are able to affirm that the best process for manufacturing the pump block is the second process, die casting with aluminum alloy. This process is schematized on figure 7.
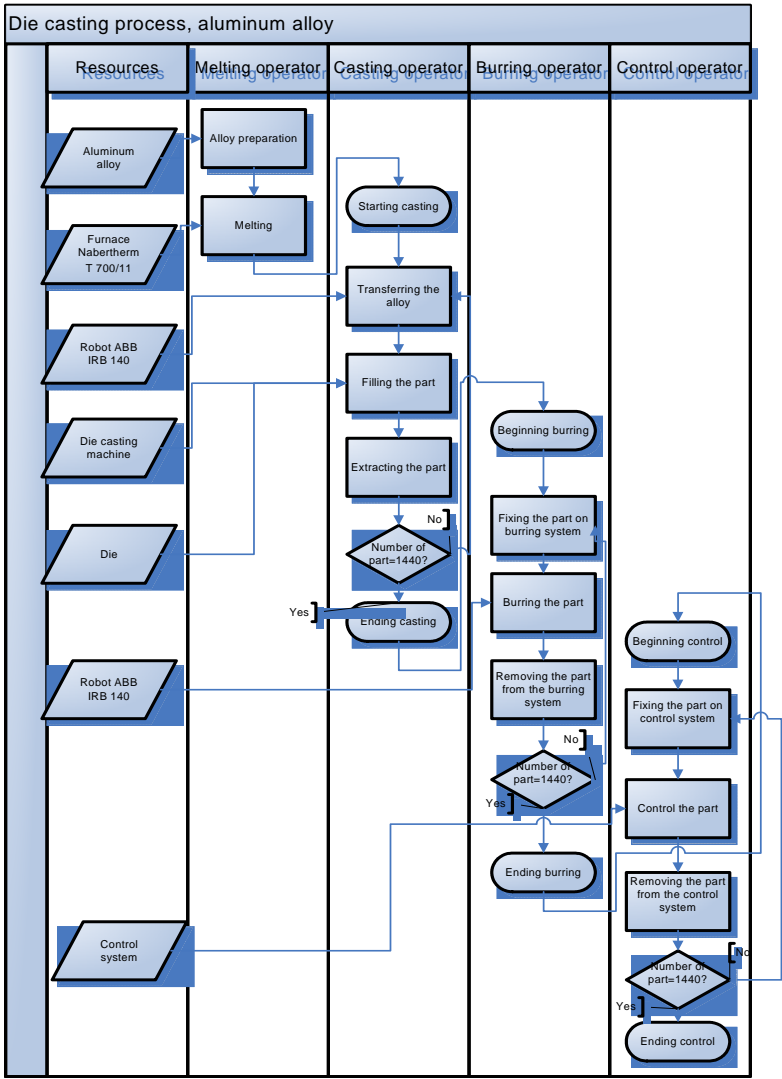
Figure 7: Process 2 for manufacturing the pump block

4. Machining process

Identification of the key parameters
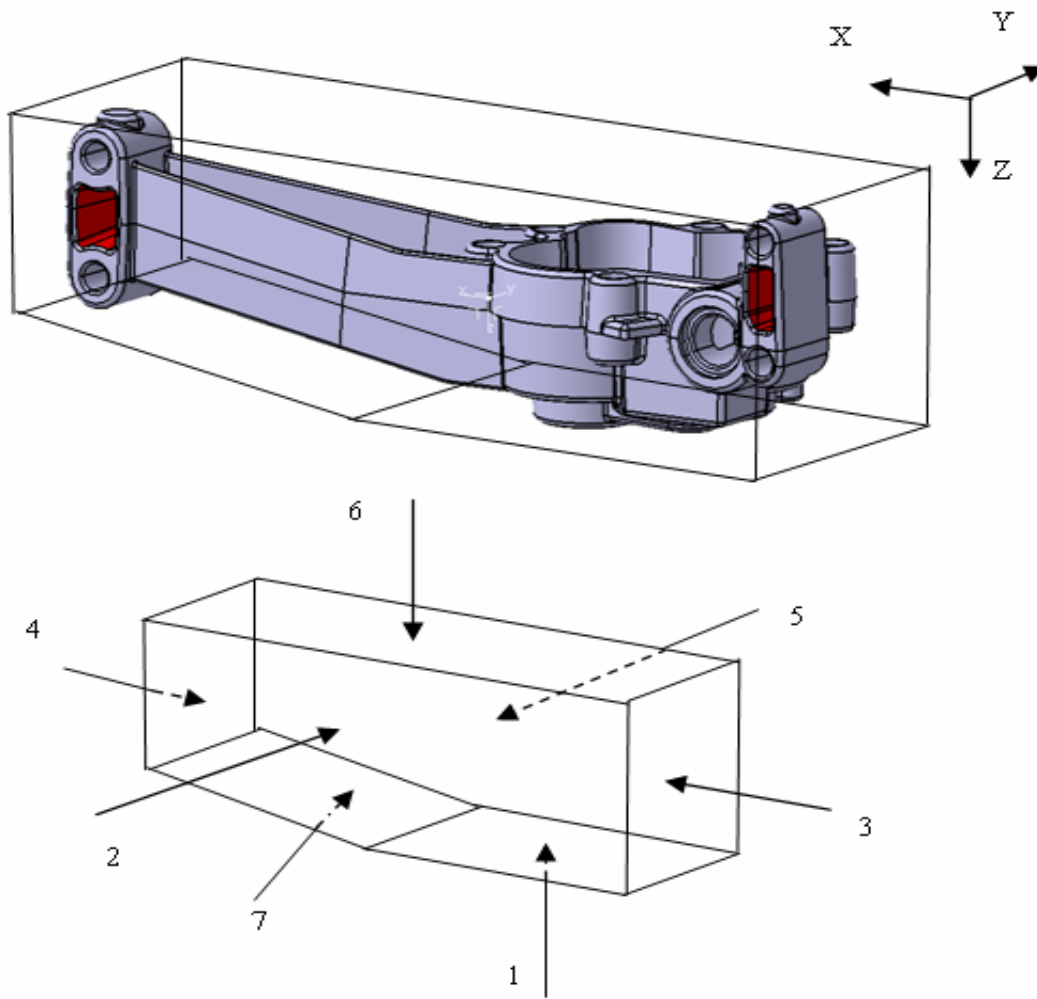
Characteristic polyhedron

A characteristic polyhedron is used to associate the geometry of a part in order to simplify the identification process of all the machined parts. The polyhedron associated by the geometry of the oil pump block has 7 sides each of these defined by the directions of the different faces of the part. The following figure 8 illustrates this characteristic polyhedron. Each side is numbered for identification of all the machinable parts in it.

There are several features in the part that have been designed for the sole purpose of positioning the part for other more important machining processes. One is a plane contact with 3 contact points while the other is a centering location contact used to center the part and measure out to all the specific distances for machinable features. The remaining 3 degrees of freedom are suppressed by the second centering point that is composed by a hole and slot.

Machinable feature

Each machinable feature of the part is defined by a geometrical shape and a set of specifications. These are normally tolerances, angles, specific dimensions, etc. These specifications can be categorized into three types: geometrical (length, diameters, angle…), technological (roughness, geometrical or dimensional tolerances…) and topological (relation between two different features). Considering these specifications, many of the features of the oil pump block will not need further machining after the forming process since they do not require precision and high quality.

There are 14 different machinable features in this part. The figure 9 shows all these features relative to one another. Table 13 shows a list of the features that need to be machined and their main geometrical and technological data.

Figure 8: Characteristic polyhedron of the SEM oil pump block showing all the numbered sides and their directions
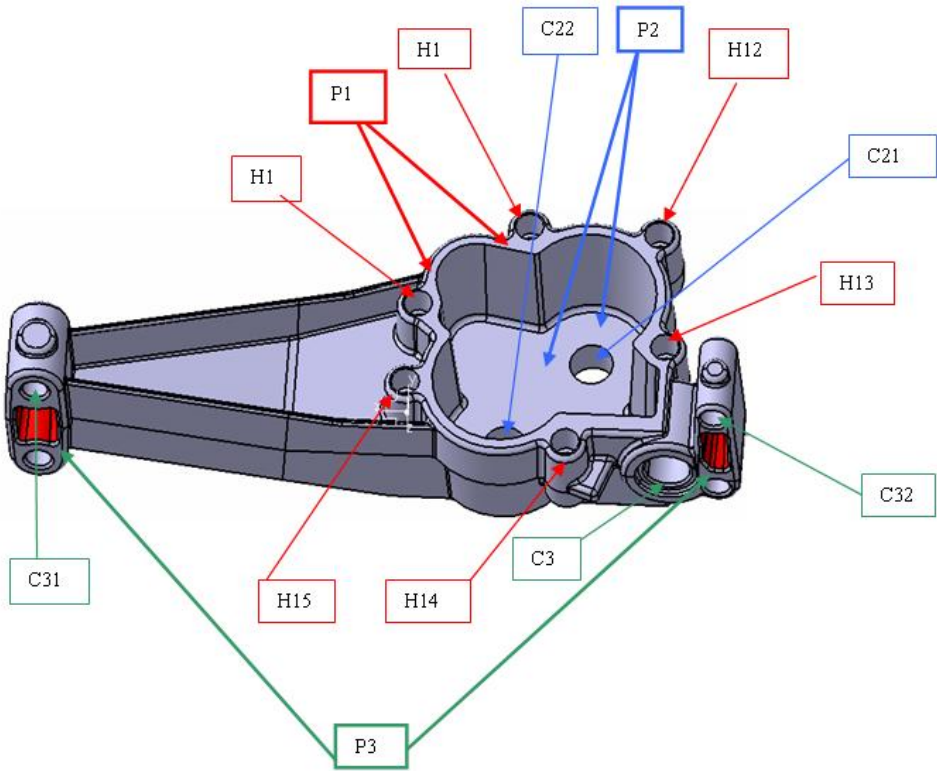
Figure 9: Features needed to be machined

Features	Feature type	Topological relations	Geometrical datas	Technological datas				
H11	cylinder + plane	starts on P1	Diameter, screw parameters	Cylindricity, perpendicularity, position				
H12	cylinder + plane	starts on P1	Diameter, screw parameters	Cylindricity, perpendicularity, position				
H13	cylinder + plane	starts on P1	Diameter, screw parameters	⊕	∅0,4	Z	V	W
H14	cylinder + plane	starts on P1	Diameter, screw parameters	Cylindricity, perpendicularity, position				
H15	cylinder + plane	starts on P1	Diameter, screw parameters	⊕	∅0,3	V	W	
				⊕	∅0,3	C		
				⊥	∅0,3	C		
H16	cylinder + plane	starts on P1	Diameter, screw parameters	Cylindricity, perpendicularity, position				
P1	plane			//	0.05	P3	C31(M)	C32(M)
				⊕	0.2	P3	C31(M)	C32(M)
P2	plane	contains C21 and C22	planeity, parralelism	⊕	0.04	P1		
C21	cylinder	starts on P2	diameter	⊕	∅0.04	P1	H15	H12
				⊕	∅0.04	C22		
C22	cylinder	starts on P2	diameter	⊕	∅0.04	P3	C31(M)	C32(M)
				⊕	∅0.04	P1	A	B
P3	plane	contains C31, C32, C33, C34, C35		planeity	0.05			
C31	cylinder	starts on P3	Diameter, screw parameters	Cylindricity, perpendicularity, position				
C32	cylinder	starts on P3	Diameter, screw parameters	⊕	∅0.3	Z	V	W
				⊕	0.4M	P3		
				⊥	∅0,02M	P3		
C33	cylinder + plane	starts on P3, ends on P2	Diameters	⊕	0.08	P3		
				⊕	∅0.4(M)	P3	C31(M)	C32(M)

Acc

Table 13: Features that are needed to be machined with their specifications

In order to define the position of axis system the homogeneous coordinates (matrix 4 x 4) is commonly used in CAD software for example, and is an efficient mathematical tool which can easily be manipulated in formal calculations tools. This matrix introduces the parameters of the local position of each feature relative to the part position (part axis system). The 12 terms which are non null or equal 1 characterize rotations (3 X 3 terms) and translations (last column) (figure 10).
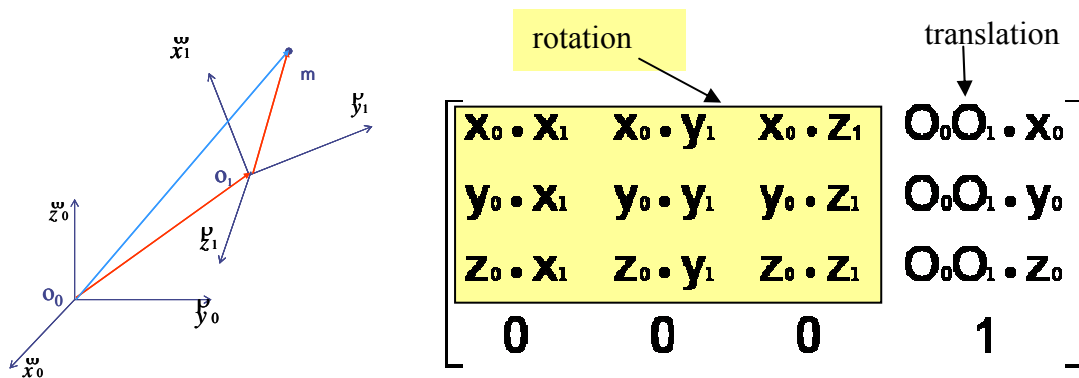
Figure 10: homogeneous coordinates

Accessibility

An important consideration for process planning is how accessible each of the features are relative to each other and their direction. The table 14 shows this relationship and their accessibility. For machining complex surfaces which can be machined en end milling, periphical milling or by parallel paths at the same height, the accessibility is given by the set of possible spindle directions (Gauss sphere , figure 11).
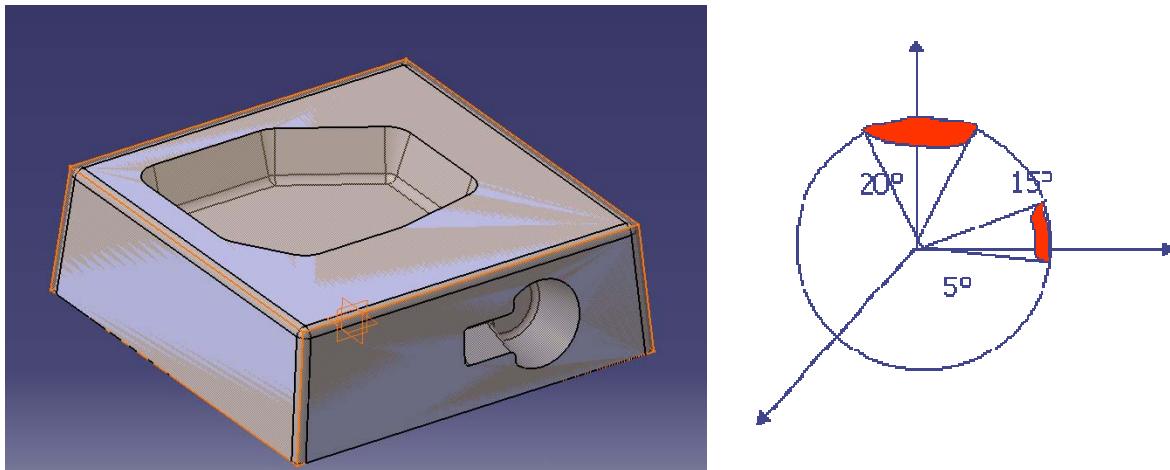
Figure 11: Gauss sphere

Features	Feature type	Feature shape	Direction	Accessibility direction	Way of machining
P1	plane	plane	Z	6 W 2 W 3 W 4 W 5	milling: surfacing
P2	plane	plane	Z	6 W 2 W 3 W 4 W 5	milling: surfacing
C21	cylinder	emerging hole with two diameters	Z	6 ∧ 1	drilling
C22	cylinder	emerging hole with two diameters	Z	6 ∧ 1	drilling
P3	plane	plane	Y	2 W 1 W 3 W 4 W 6	milling
C31	cylinder	emerging hole with a screw and a chamfer	Y	2	Driling + screwing
C32	cylinder	emerging hole with a screw and a chamfer	Y	2	Driling + screwing
C33	cylinder + plane	one-eyed hole with two diameters	Y	2	Driling

Features	Feature type	Feature shape	Direction	Accessibility direction	Way of machining
H11	cylinder + plane	emerging hole with two diameters, a screw and a chamfer	Z	6	Drilling + screwing
H12	cylinder + plane	emerging hole with two diameters, a screw and a chamfer	Z	6	Drilling + screwing
H13	cylinder + plane	emerging hole with two diameters, a screw and a chamfer	Z	6	Drilling + screwing
H14	cylinder + plane	emerging hole with two diameters, a screw and a chamfer	Z	6	Drilling + screwing
H15	cylinder + plane	emerging hole with two diameters, a screw and a chamfer	Z	6	Drilling + screwing
H16	cylinder + plane	emerging hole with two diameters, a screw and a chamfer	Z	6	Drilling + screwing

Table 14: Features with their direction and accessibility information

Features description

•   H- features are composed of two holes: one screwed hole of diameter 8mm and depth 30 mm and a second hole of diameter 11mm and of depth 11mm. The edge between the two holes presents a chamfer of angle 45°. H13 and H16 have an extra quality requirement of H7 quality.

•   P- features are planes that need to be milled. The casting process gives a relatively high tolerance so not a lot of milling is required.

•   C- features, more specifically C21 and C22 are emerging holes with two diameters 22.6 mm at a depth of 15 mm which has an additional reaming operation for quality purposes and 28 mm depth of 0.5 mm. C31 and C32 are holes with diameter 11 mm at a depth of 11 mm. The required quality is H7, therefore a reaming tool is also required. C33 is usually the correct dimension right after casting but needs a reaming tool to smooth and assure precise dimensions. .

In order to compute the most cost effective way to machine these features several parameters need to be compared. One of these is tooling. What tools are used to machine each of the parts. These can be ready made tools that are replaced when needed or tailor made tools that are made specifically for this feature. Each has their advantages and disadvantages.

Ready made tools are easy to purchase and the replacements are easy to acquire and they tend to be cheaper than tailor made tools. However, it may require more tooling time to get the same quality as the tailor made tools. In addition, it may require multiple tools for many features whereas a tailor made tool can perform all the requirements in one motion. In order to choose the correct tool for each feature, some calculations were made based on the dimensional needs of each feature.

Precedence constraints

The first precedence constraint is given by the set-up. The number of set-up has to be limited because reference surface changes introduce a loss of time and accuracy. The study of the accessibilty direction table or part sphere Gauss allow to determine the best set – up (Yao S. and al. 2004).

The geometrical interactions and the technological constraints (localization, parrallelism, perpendicularity) introduce precedence constraints. Below some examples of machining interactions:

•   H1i and P1: the solution will be to drill H1i after surfacing P1. By using this sequence, the surface P1 will be sharp and clean, so the drilling tool won't be disaxed on the beginning of the operation. After the drilling of Hi, some unexpected defaults must appear on P1 level, but those latters will be eliminated after chamfering Hi∩P1.

•   C2i and P2: the roughness of C2i is higher than P2 one; so we will drill C2i first

•   if two surfaces intersect themselves and have high roughness, whenever, we machine those features, the common area will be surfaced twice.

Tool choice and processing time

For each machinable feature (holes, planes, slot..), basic operations (centering, drilling, reaming, rough surfacing, finish surfacing..) tools needed are determined from tool manufacturers and the processing time are computed. Some examples are given table 15.

Operation properties		1st hole	** needs to be screwed to 8mm
			units
hole diameter	d	7.70	mm
hole depth	L	30.00	mm
rotational speed	n	117.82	rev/sec
feed per revolution	fr	0.30	mm
feed per tooth	ft	0.15	mm
chip area	A	0.58	mm^2
volume removed	vlr	1396.99	mm^3
		1.40	cm^3
Metal Removal Rate	MRR	1.65	cm^3/sec
		98.75	cm^3/min
Cutting fluid flow	q	1.40	l/min
Cutting time per	t	0.85	sec

hole

Force analysis

specific force	Ks	1500.00	N/mm^2	W sec/cm^3
ultimate tensile stress	UTS	530.00	N/mm^2	
Tangential Force	Ft	866.25	N	
Axial Force	Fa	866.25	N	
Torque	T	3.34	Nm	
Power	P	2468.83	W	
		2.47	kW	

Table 15: Calculated values for H 11, H121, H14 , H15 machined feature

The milled planes that are needed to be milled in this part are very different and need very distinct tools. P1 cannot be milled with a conventional face-mill milling machine because it can cause tool collision with the side of the part. Therefore end-milling is what can be used to remedy this problem. With this tool not only the bottom plane P2 but the sides can simultaneously be milled to the correct dimension. Some extra properties were chosen for the tool to make the process more efficient. These include properties in design, material, and coating.

• Design - Four fluted tool : produce finer finishes and last longer than two or three-flute tools. Compared to two-flute tools, they remove metal faster and can be fed up to two times faster.

• Material - Solid Carbide : can be run three to ten times faster than high-speed steel. In addition, it is harder than high-speed steel for better resistance to abrasion and high cutting temperatures. The tool is offered in micrograin and premium sub-micron-grain grades.

• Coating - TiCN : also known as Titanium Carbonitride. It performs almost as well as carbide in difficult-to-machine materials such as aluminum, aluminum alloys, cast iron, alloy

steels, stainless steel, carbon steel, and brass. It provides excellent wear protection in the most abrasive materials.

For high production it can be interesting to use tailored made tools (storied tools for example) for which the price is higher but high productivity is get.

Definition of type of movement per feature

For each possible tool direction for each machinable feature, the type of movement is specified (F: fixed, PT: positioning, PX: paraxial, C: continuous path control); it is directly linked to the choice of components (kinematic, motorization..) in the case of dedicated manufacturing system or the performance needed for a classical numerical control machine tool and hence their cost. Table 16 gives an example of possible directions of accessibility and movement needed for each feature.

Feature	Positionning	Machining process	Anteriority	Accessibility direction	Motion X	Motion Y	Motion Z
P1	1	end milling	/	6	Pt	Pt	Pt
H11^H12 ^H14^H15	1	drilling	P1	6	Pt	Pt	Px
H13^H16	1	drilling	P1	6	Pt	Pt	Px
P2^C21 ^C22	1	end milling + drilling	P2	6	Pt	Pt	Px
P3	1	face milling	/	6W3W4W1W7	Px	Pt	F
					In case of accessibility 6		
C31^C32	1	drilling	P3	2	Pt	Px	F
C33	1	reaming	P3	2	F	Px	F

Table 16: Possibilities to machine each feature

Sequencing the process

From the data presented on previous sections (topological and geometrical interactions), we can define the possible process plan (sequences of operation). These plan can be represented by a graph or equation written with temporal logic operators:

- V: OR, Λ: AND, W: OR exclusive

- S ( ) indicates that the terms in brackets are produced simultaneously (staged or associated tools, spindles working simultaneously on a single part);

- M (A) indicates what to expect to make A.

By using temporal reasoning, we have:

- P1ΛM(Hi)
- C2iΛM(P2)
- $((C2i\Lambda M(P2)) \Lambda M^2(P1\Lambda M(Hi)) \Lambda M^3 (P3 \Lambda M (C3i))) \ W ((C2i\Lambda M(P2)) \Lambda M^2 (P3 \Lambda M (C3i))) \ \Lambda M^3 (P1\Lambda M(Hi)))$

Designing the manufacturing system (D'Acunto A., and al. 2007)

As soon we have the process plan it is possible to design the operative part of the dedicated machining system with elementary modules. Due to the new market constraints and the product design evolution (it belongs to a family e.g. cylinder head, engine block), Reconfigurable Manufacturing System (RMS) has received increasing attention as a means for realizing both the flexibility and productivity.

In order to be able to design the manufacturing system, all the different requirements (technical, economical, production, line balancing) of the system have to be considered. Every choice is linked with a constraint and introduces a new constraint that has to be considered.

The design process must follow two main steps: reduce the number of possibilities (destructive choice define from the strategy of the company, the cost of the manufacturing, the characteristics of the part to manufacture, the technological knowledge) and then undertake several simulations (figure 12) to compare the performances by multicriteria analysis.

So a lot of characteristics (or criteria) can be defined to evaluate the system some of then can be easily quantified others their quantification is mainly subjective, for example:

- Technical: size, accuracy, speed, power, type of energy needed (electrical, hydraulic, and pneumatic)…

- Production: number of parts produced per day, flexibility (type of part produces), line balancing, reconfiguration average time for each product variation, integrability, maintenance, evolution ability, customisation…

- Economical: cost, maintenance cost, functioning cost

- Human factors: is the system easy-to-use? Number of technicians aware with the using of the system, ergonomy….

The kinematics compatibility is one of the parameters to be included in the design of the manufacturing system. For each feature to machine, a set of basic modules will be assigned to the manufacturing process. The main point is to define the machining process with elementary modules. So, how many holes do we have to drill simultaneously? How many cells does the machining process require?. We have to use elementary machining cells, to shape a RMS process. The different elements we can have the use are: Drilling cells, Multi-drilling heads, Tooling, Actuator cells, Fitting tools, Supports on which elements are attached, so we have a library of these elementary devices which allow designing the virtual manufacturing system.

At this stage, we must face the abundance of possible configurations and make a choice. The number of possibilities is depending to the chosen granularity, here it is the machining module. A machining module is an assembly of basic component: a support, one or several actuator(s), translation cell(s) and tool(s). Position of each module on the line depend of technical and economical constraints such as: the available volume, the kinematics links to be created, the possible vibrations during milling, the module price, the flexibility required or foreseen. The duration of each operation is given by the software...So several configurations can be built and their performances compared by multi-criteria analysis.
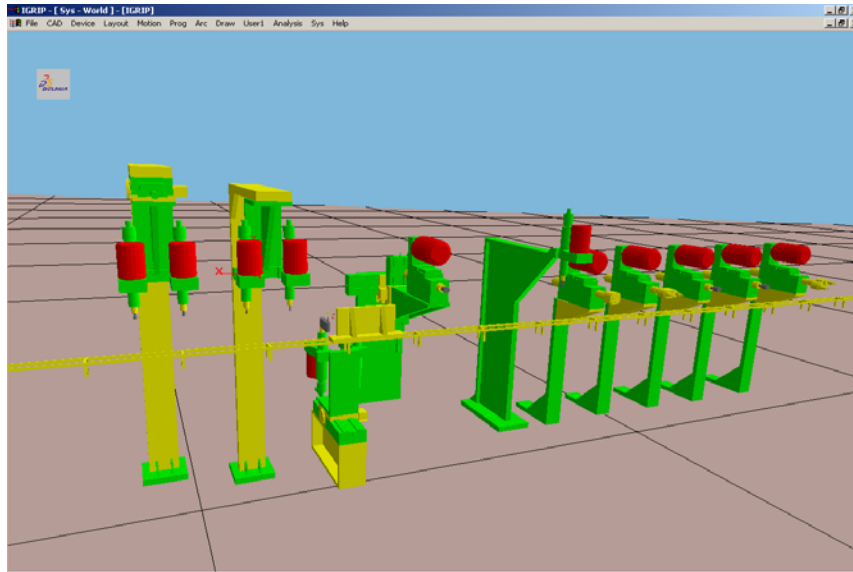
Fig. 12 : Manufacturing line CAD model

5.   Conclusion

Virtual Manufacturing gives a new dimension to manufacturing design (process plan and manufacturing system) by dramatically reducing times at each step of product life cycle. New tools based on a structured methodology allow to provides aid in decision making for process engineering, thus helping reduce the time of production engineering. The keys points are:

- to avoid choices too early which can restrict the set of solutions,

- used models and tools which underline relevant parameters,

- part don't need to be completely define in order to begin the process plan design phase, process plan is built simultaneously with the final part shape,

- take into account simultaneously technical, economical and logistical constraints,

- performance analysis using multicriteria analysis.

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