Proceedings of the 15th International Conference on Manufacturing Systems – ICMaS
Published by Editura Academiei Române, ISSN 1842-3183

“Politehnica” University of Bucharest, Machine and Manufacturing Systems Department
Bucharest, Romania, 26 – 27 October, 2006

INTEGRATED PRODUCT AND MANUFACTURING PROCESS: VIRTUAL MANUFACTURING OF RECONFIGURABLE MANUFACTURING SYSTEMS

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Abstract: *In the frame of concurrent engineering the design of the parts, the production planning, even 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. The need of a short reconfiguration time leads to the concept of Reconfigurable Manufacturing Systems (RMS): using those systems, the manufacturer only uses elementary cells (such as milling cells, supports, tooling, etc ...) which can be easily and quickly replaced as soon as the demand changes. Besides, this higher reconfiguration speed can be improved by using Virtual Manufacturing: the manufacturer can design, draw and simulate the line and its evolution in terms of flows and costs. It is a powerful help to evaluate the best performance if several configurations are possible before the system is built, hence a gain of time. In the frame of virtual manufacturing of reconfigurable manufacturing systems, this paper will deal with creating and simulating machining systems based of an industrial part (a pump block in our case) and using a computer aided engineering software (DELMIA- Dassault Systemes).*

Key words: *manufacturing process, concurrent engineering, manufacturing reconfigurable systems, virtual manufacturing.*

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 [1, 2] 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 Fig. 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

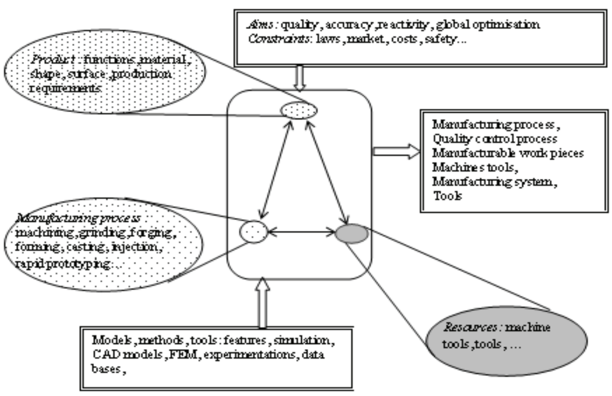

Fig. 1. Reference diagram of our approach [8].

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 processes (forging, casting, stamping, machining, assembling, fast prototyping…), production resources (machines, tools…), and conditions for implementation (setting and holding in position, 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, etc.).

Here we are interested in developing a production system which constitutes a specific, but unique product. It must mass produce products which are in the same family but which may evolve according to technological development or market demand. A great deal of work is being done on production system design, but is mainly concerned with logistics aspects (installation, scheduling) based on technical and temporal data (sequences, times, production resources) provided by the methods department. Work on designing the operative part of production systems is still limited [3, 4, 5, 6].

We therefore propose a methodology to help in defining flexible production architecture for use in mass production machining with the intention [7]:

- of integrating the manufacturer's expertise based on a grouping strategy using production features;
- of integrating "flow shop" type linear mass production;
- of making it possible to formalize concepts by including productivity, cost, flexibility and quality parameters.

The selected architecture must meet:

- technological requirements needed to produce each machining feature (respecting surface condition, geometric and dimensional tolerances) and equipment capability (precision, torque, power, speed...);
- economic constraints;
- logistics requirements: quantity, series, lead-times.

In a coherent approach based on a methodology, models and tools.

In this paper we present an example of using our methodology on an industrial part and we show how to design the manufacturing system, then the system is modelled on computer aide engineering software in order to simulate its behaviour.

2. VIRTUAL MANUFACTURING OF RECONFIGURABLE MANUFACTURING SYSTEMS

In order to reduce designing times and to give a help to choose the most suitable system for a specific process, Virtual Manufacturing appears helped by the developments of numerical methods for computing. We quote that Virtual Manufacturing is present all along the product cycle, hence its importance; the company must share its knowledge.

Besides the concept, Virtual Manufacturing is based on numerical tools, such as:

- global database: all the ownerships of the company are listed and the staff can easily design or improved the factory with available stuff;
- 3d manufacturing simulations: it enable to plan, detail, analyse and simulate the product life throughout the manufacturing engineering cycle;
- logistics softwares (*e.g.* erp): it matches all the actors of the product, from the provider of the provider to the customer of the customer.

Manufacturing global demand and rapid changes in process technology (*e.g.* the evolution of the product, of the quantities, of the variety of products) require creating production systems easily upgradeable and into which new technologies and new functions can be integrated in the fields of manufacturing (mechanics, controls, flows and so on). Thus, there is a growing trend to produce smaller quantities with frequent small variations within a product family, so called mass customisation. For example, if the customer orders a variation of the number of holes on an engine block and/or an angular variation of those latter's the manufacturer must change his process as quickly as possible.

Before Reconfigurable Manufacturing Systems (RMS) appearing, we only could process with two extreme kinds of Machining Systems: Dedicated Systems (high productivity) and Flexible Systems (high flexibility); RMSs are placed somewhere in between those two boundaries. A solution is to use only elementary cells (machining, actuator and control cells) and to reconfigurate them according to the demand of the customer.

Those systems are something in between - what we call customized flexibility. The idea is to design the production system around the concept of part family to achieve a lower cost and therefore a higher production rate with the required flexibility: basic process modules (hardware and software) are incorporated and can be rearranged or replaced quickly and reliably. So customized flexibility is provided for a particular part family. So rather than replaced, they can be improved, upgraded, etc. The appeal of reconfigurable manufacturing is to meet market demand with the right amount of the right product at the right time in an era where product development time is shrinking. So a given RMS configuration can be dedicated, flexible or in between. They permit a reduction of lead time for launching and reconfiguring systems, and a rapid manufacturing modification and quick integration of new technology or specification. These systems will not run the risk of becoming obsolete, because they will enable the rapid changing of system components and the rapid changing of components and the rapid addition of application-specific software modules. They can be continuously improved by integrating new technology and be rapidly reconfigured to accommodate future products and changes in product demand rather than scrapped and replaced. So RMS are placed somewhere between two extrema: dedicated and flexible systems. On one hand, dedicated systems sometimes do not operate at their full capacity, which create a loss. On the other hand, the flexible capacities of FMS maybe won't be used during the life time of the machine. But with RMS technology, these two types of waste will be eliminated. So, RMSs combine the advantages of DMS and DMS while avoiding their disadvantages.

3. APPROACH FOR DESIGN AND CONSTRUCTION OF RECONFIGURABLE MACHINE-TOOL SYSTEM

3.1. Design Process

To introduce and present the approach for design and construction of reconfigurable machine-tool system, it is quite convenient to use the Structured Analysis and Design Technique model (Figs. 2 and 3).

- *first level: To define the system*
- *second level: To Analyse of the part characteristics.*

3.2. Presentation of the part to machine

The part to manufacture (in fact the machining process) is an oil pump block used on a truck and made by SEM. The process planning for manufacturing of this part using RMS will be designed, using the methodology previously introduced. Each step of the RMS shaping process will be explained according to the reference method and illustrated in the case of the oil pump block.

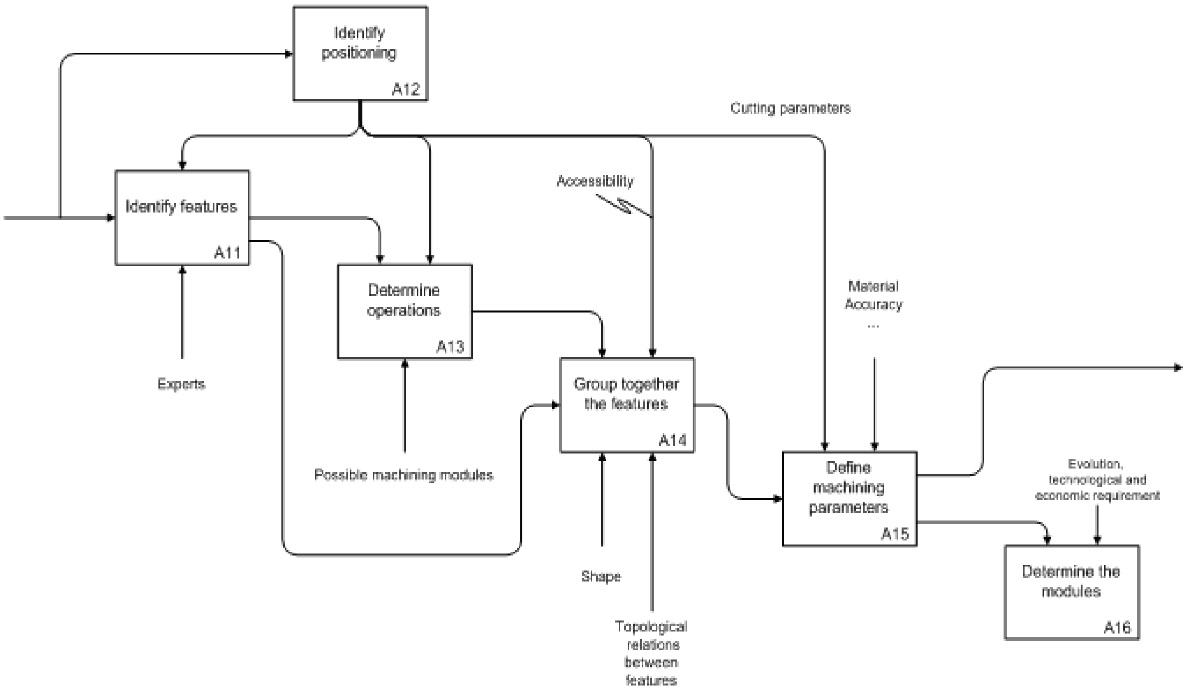

Fig. 2. Level A0 of the approach for design and construction of reconfigurable machine-tool system.

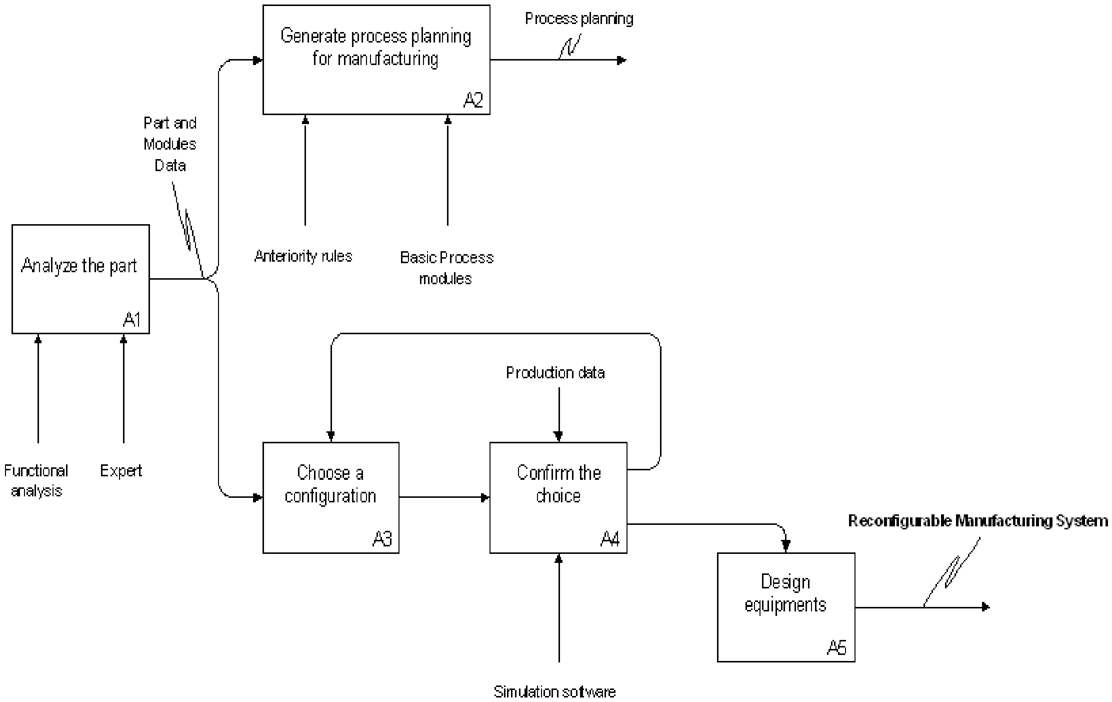

Fig. 3. Level A1 of the approach for design and construction of reconfigurable machine-tool system.

In order to design a RMS, it is necessary to know some data concerning the part to be made and the production requirement of this part. This design process has to take into account the changes in part characteristics that may arise in the future and which would induce a change in the configuration of the manufacturing system. We can distinguish three types of data related to the part.

Technical data relative to the part. Geometrical data, which are defined on the drawing of the part or in a CAD file: shape of the part, dimensions, characteristic polyhedron, accessibility directions, dimensional or geometrical tolerances, etc.

Technological data concerns the features to be machined (hole, plane, chamfer, screw…), the features to be molded or the features used for positioning the part. Technical data also concern the required tolerances for each feature (positioning, shape) and the required roughness. It also deals with the material used, the cutting parameters and the mass of the part.

Economic and Logistic data. These data describes the required production capacity, the type of production (mass production, unitary production…), the repetitiveness of the production, the allowed time, the number of daily working hours, the allowed budget…

3.3. Analysis of the part characteristics: Identification of the positioning of the part

The first step in the design of the machining process is the identification of the geometry of the part. To identify this geometry, it is useful to find a characteristic polyhedron of the part. This polyhedron is defined by the directions of the faces of the part. In the case of the oil pump block, the polyhedron has seven faces. Fig. 4 shows the characteristic polyhedron of the oil pump block.

Using the polyhedron, the identification of the positioning of the part required the definition of the faces of the part which will be used to position the part during the machining process. The choice of the positioning of the part has a great influence on the manufacturing system's configuration.

The analysis of the blank part is useful in the case of the SEM oil pump block (Fig. 4). Indeed, five features on the face number 1are not to be machined and have been designed for the positioning of the part.

The positioning of the part has been included in the design of the part. The blank part presents three planes distributed homogeneously around the part and which allow a plane contact that suppress three degrees of freedom. The blank also provides two features, a hole and a slot which compose a centering plus locating contact that suppress the three remaining degrees of freedom.

Identification of the features to be machined

The analysis of the part requires the definition of the features to be machined. According to [2] feature is defined by a geometrical shape and a set of specifications relative to a machining process. A feature has attributes which are of three types: geometrical (length, diameters, angle…), technological (roughness, geometrical or dimensional tolerances…) and topological (relation between two different features).

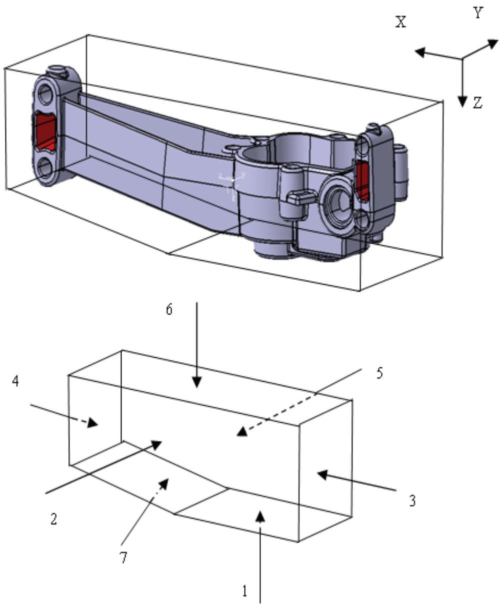

Fig. 4. Characteristic polyhedron of the SEM oil pump block.

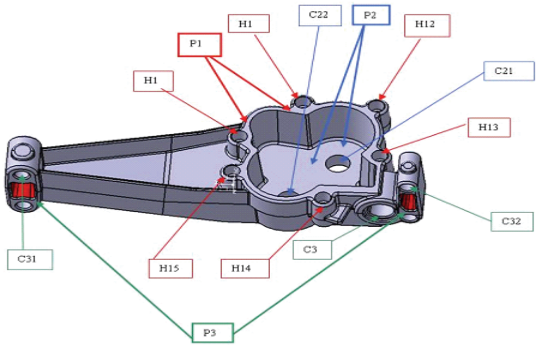

Fig. 5. Features to be machined during the SEM oil pump block's manufacturing process.

Concerning the SEM oil pump block, some features will not be considered as to be machined because their geometrical, technological attributes do not require the precision and the quality of machining process. Some of these features are used for the positioning of the part and some others are used for geometrical positioning of features to be machined. The features to be machined are shown on Fig. 5. Table 1 shows the list of features to be machined and their main geometrical and technological data.

The identification of the interactions between the features is useful for the process planning for manufacturing. It allows the identification of anteriority constrains and is useful when determining the possibilities to work simultaneously.

Table 2 shows the interactions between all the features, those to be machined and those not to be machined.

Determination of all the possibilities to machine each feature

Each machining process associated with each feature has to be identified. Some feature may be associated with many machining process. In this case, we have to consider the anteriority constrains and the fact that some features might be machined simultaneously.

During this stage of the RMS shaping process, it is also important to define the motion required to machine the feature in order to define, later, the kinematics of each process module. To present this motion I will use the following abbreviations: Px represents a real machine axis, Pt represents point to point motion and F represents a fixed axe (no motion). Table 3 presents a way of machining each feature of the SEM oil pump block. Fig. 6 shows the CAD model which is only useful for designing manufacturing system, so only the machining features have been extrated from the geometrical CAD model.

Machining parameters

During this stage of the RMS process shaping, we know the following data concerning the part: the set of feature to be machined, the definition of these features (types, attributes, interactions, etc.), the machining process associated, the material characteristics, the required precision, the positioning of the part, the required tools' types and the type of motion for each process module. The aim at this level is to determine the machining parameters: cutting

Table 1

List of features to be machined and their main geometrical and technological data

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	⊕	ϕ0.4	Z	V	W
H14	cylinder + plane	starts on P1	Diameter, screw parameters	Cylindricity, perpendicularity, position				
H15	cylinder + plane	starts on P1	Diameter, screw parameters	⊕	ϕ0,3	V	W	
				⊕	ϕ0,3	C		
				⊥	ϕ0,3	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	⊕	ϕ0.04	P1	H15	H12
				⊕	ϕ0.04	C22		
C22	cylinder	starts on P2	diameter	⊕	ϕ0.04	P3	C31(M)	C32(M)
				⊕	ϕ0.04	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	⊕	ϕ0.3	Z	V	W
				⊕	0.4M	P3		
				⊥	ϕ0,02M	P3		
C33	cylinder + plane	starts on P3, ends on P2	Diameters	⊕	0.08	P3		
				⊕	ϕ0.4(M)	P3	C31(M)	C32(M)

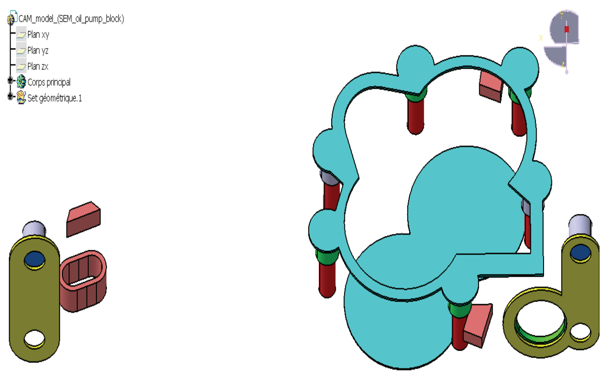

Fig. 6. CAM model of the SEM oil pump block.

conditions, tools definition, tool trajectory, machining time required for each feature. The classifical method for process planning choice is used [9].

Only the features to be machined have been modeled as well as the features used for the positioning of the part.

3.4. Designing the manufacturing system

Definition of the process modules

This step of process planning for manufacturing consists in the design of the operative part of the machining process. Indeed, we need here to make choices concerning the technology of the RMS' components.

Table 2

Technological relations between features

Feature	Technological data					Technological interactions – Features to be machined														Technological interactions – Features not to be machined		
						H11	H12	H13	H14	H15	H16	C21	C22	C31	C32	C33	P1	P2	P3	V	W	Z
H11																						
H12																						
H13	⊕	Ø0.4	Z	V	W																	
H14																						
H15	⊕	Ø0,3	V	W																		
	⊕	Ø0,3	C																			
	⊥	Ø0,3	C																			
H16																						
C21	⊕	Ø0.04	P1	H15	H12		⊕			⊕			⊕				⊕					
	⊕	Ø0.04	C22																			
C22	⊕	Ø0.04	P3	C31(M	C32(M		⊕			⊕				⊕	⊕		⊕		⊕			
	⊕	Ø0.04	P1	H15	H12																	
C31																						
C32	⊕	Ø0.3	Z	V	W														⊕ ⊥	⊕	⊕	⊕
	⊕	0.4M	P3																			
	⊥	Ø0,02M	P3																			
C33	⊕	0.08	P3											⊕	⊕				⊕			
	⊕	Ø0.4(M)	P3	C31(M	C32(M																	
P1	//	0.05	P3	C31(M	C32(M									⊕ //	⊕ //				⊕ //			
	⊕	0.2	P3	C31(M	C32(M																	
P2	⊕	0.04	P1														⊕					
P3																						

Table 3

Technological relations between features

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

The first thing to do is to define the kinematics needed for each of the machining operations. Table 3 which shows the possibilities to machine each feature and the required motion is one of the data needed to achieve this process. The definition of the kinematics is done using HTM (Homogeneous Transformation Matrices). HTM are four by four matrices which represent the kinematics between two baselines. Fig. 7 shows an example of HTM matrix to define the position of two features in the part baseline.

The remaining stage to achieve is to define the set of components which will achieve the required kinematics. The kinematics compatibility is one of the parameters to be included in the design of the operating part of the manufacturing system. For each feature to machine, a set of basic modules will be assigned to the manufacturing process. Each feature need one or several Degrees Of Freedom (DOF) and is defined using its MHT. The compatibility of kinematics for a set of modules, to achieve the machining of a feature, means that the matrix product of the MHT of each component is equal to the required MHT of the feature.

Viability of the kinematics: MHT = M1. M2. M3. … Mn, where Mi is the homogeneous matrix that describes the kinematics of ith basic module.

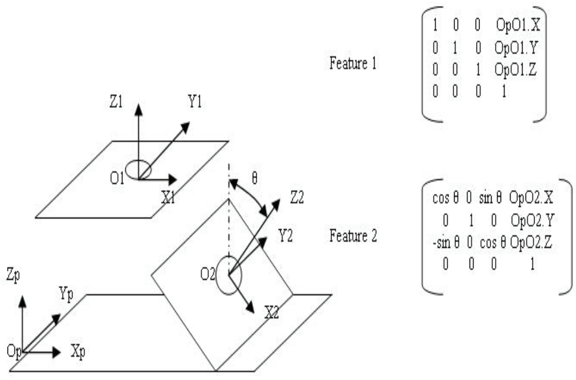

Fig. 7. Information defining feature: position in the part baseline [7].

Multiplicity of possible configurations

At this stage, we must face the abundance of possible configurations and make a choice. In the case of RMS the number of possibilities can be much bigger than for other techniques, depending on the chosen granularity. Granularity is the type of basic modules. A big granularity for a RMS means that a module which is a component of the system can be an entire digital control machine tool. According to this point of view, an entire workshop composed of machine tools and transfer lines can be considered as a RMS.

In the case of this paper, the granularity is not the same as in the previous example and the basic modules which are components of our system are: translation cells, milling, turning or drilling cells, tools, supports… In fact the granularity is chosen such that each component of the system can be associated with a basic function: to shift, to position, to support, to separate. 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. Figs. 8 show several possibilities of manufacturing modul configuration.

Methodology to choose the configuration

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.

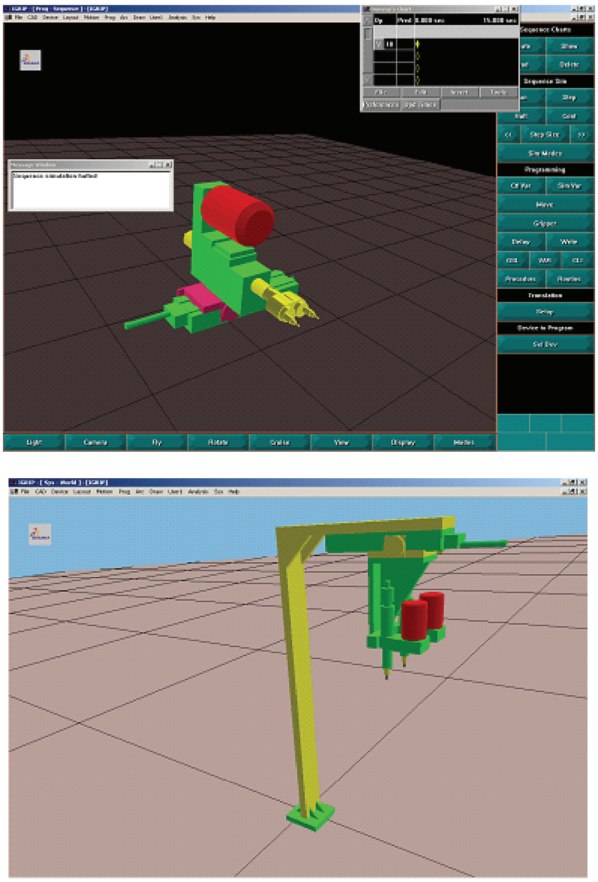

Fig. 8. Possible moduls configurations.

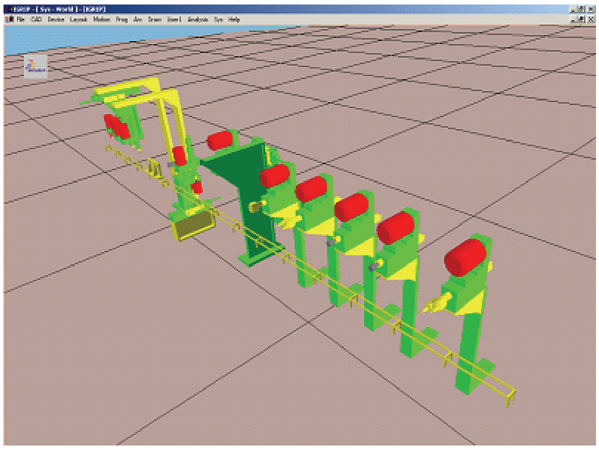

Fig. 9. Manufacturing line CAD model.

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 (Fig. 9) 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….

4. CONCLUSION

Virtual Manufacturing gives a new dimension to manufacturing design by dramatically reducing times at each step of product life cycle. But new tools seem to be developing by research centres to improve the numerical methods and tools used based on a structured methodology:

- analysis of parts.
- identification of machining features.
- definition of machining and movement components.
- choice of several architectures.
- simulation of different configurations.
- performance analysis following multicriteria analysis.

This type of methodology, to which simulations of kinematics or dynamic performance of the equipment and flow can be added, provides a tool to aid in decision making for process engineering, thus helping reduce the time and cost of production engineering.

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