MODELING AND SIMULATION OF A MANUFACTURING ENVIRONMENT

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Abstract. *In order to analyze and optimize the proper interoperations of a flexible manufacturing cell, named "CELFLEX", some modeling and simulation program applications are presented here. The followings programs and devices were applied to the manufacturing system: real time Petri Nets to analyze and control the production interactions , discrete events simulation programs, a 3D virtual reality immerse environment engaged with the real robot, Turbo PrologV2.00 knowledge rules analysis, real time expert G2 Gensym , a dedicated real time cell electronics emulator , 3D mechanical parts design and representation with SolidEdge 2004, the 3D SolidWorks 2005 program allowed to simulate the 5 axes CNC MT tool space movement animation , the 3D CNC tool path program for the 5 axes machine tool was programmed with Surfcam 2005 and the EMC2-Axis with Linux Ubuntu 6.06.*
Keywords: *Discrete simulation, expert systems, 3D object representation, robotics animation, CNC programming*

1. INTRODUCTION

The Project Leader (PL) has visited several international sites concerning with manufacturing cell research, developing, and industrial applications. So he could gathered up-to-date information about the main trends on this subject. The first visited unit was the ISW Institute of Stuttgart University-Prof. Stute (1981), followed by the Brazilian-Italian Center in Rio de Janeiro (1983), the Vuste Institute in Praga (1984), the Comau Cell at Milano Fair (1987), the FMS facilities at the Universidad Politecnica de Madrid , Aracil and Puente (1993), the FMC of INSA Lyon Institute, Jutard (1993), and the Institute for Robotics and Intelligent Systems–IRIS USC, Koshnevis (1997). The representative sites among the argentine cell manufacturing facilities are: the two Comau Cells at CTA Center (1988) and Fiat Auto (1991) both in Cordoba city, the assembling spot welding Cell at Ford Buenos Aires (1994) the Cefodti Center at the Universidad Tecnológica Nacional-UTN, Buenos Aires (1994) and the tutorial FMS System at the Instituto Nacional de Educación Tecnológica (INET) in Buenos Aires (2000). With this acquired background experiences, the PL an his team decided to build up two experimental flexible manufacturing cells (FMC). With the Bid-Conicet #83 budget support, an industrial purpose cell composed by an American CNC mill, a Promecor CNC lathe and an arc-welding Cloos Romat robot was assembled. The other one is a research and developing (R&D) manufacturing cell named "Celflex" integrated by two robots: RSA-1 and RSA-2, and two computer numerical control machine tools (CNC MT) called Elinon 1 and Elinon 2 (this under construction), presented in the Figure 1. Its main objective is to obtain a R&D integrated operational environment intended for manufacturing raw work-pieces in a random way, just as it is found in a small batch production. Figure 2 shows the cell pyramid hierarchical simulation and control layout. Modeling and simulation are the first mandatory steps for a proper analysis conducted to an optimized system operation.

2. MODELING AND SIMULATION METHODOLOGY

The methodology adopted is shown in fig. 3, following these steps: the first trials were made with the Petri Nets modeling an simulation solutions. Starting with a hardware implemented with 4000 series Cmos integrated circuits and following the theoretical modeled phenomenon established by Peterson (1981), Reisig (1985) and Silva (1988), Morán (1990) developed a basic simulator which was able to analyze a classic production-consumer-storage cell layout.
Later on, Trombotto and Maidana (1994) developed a real time graphic simulator written in C running on a DOS PC, so a FMC Petri Nets model bottleneck, firing sequences, place-to-transition incidence and transition input–output relationship matrices could be analyzed. The second trial concerns with the control system modeling built on Data Flow Diagram (DFD) basis. Morán et al (1995) followed the methodology chosen for the modeling problem based on the proposals of Gane / Sarson (1988) and the Yourdon Press team (1993) for system analysis on account of its simplicity, potential uses, high degree of logical abstraction and the possibility of achieving a full pattern of details. This FMC simulator and control was implementing using the language Turbo Prolog V2.00 (1986) . Rogers (1986) stated that this Prolog program is a way of representing knowledge. The different FMC states of each component are shown dynamically in real time, and the development of the manufacturing process can be clearly followed.

The third trial was a FMC discrete simulation model. Following the Bobilier (1976) and Lenz (1985) paradigms, the three steps in the design of a FMC systems are “aggregation”, “simulation” and “animation”. Among several simulation packages oriented to the problem e.g.: MAP/1 from Pritsker & Associates and Spar/Mast from CMS Research, the team chose the Simfactory II.5 / Simprocess V 6.2 (1994) from CACI, U.S.A. Once the simulation trials have shown the overall performance, a strategic design decision can be drawn. Apóstoli et al (1995) reported that it could help them to find out the best robot velocity ratio, so a balanced design for the experimental robot RSA-2 was obtained. The team also tested the USC-Koshnevis (1994) EZSIM DOS based discrete event programming. The four trial concerns with Virtual Reality (VR) 3D simulation and real time control. According to Ferraro (1995), Luciano (1997) designed and built a VR program written with Criterion Render Ware V3.00, allowing a human operator to analyze the manufacturing site through interactive immerse environment. This VR environment belongs to an integral informational system which consists of five big modules: robotic flexible cell programming , production intelligent execution, simulation, real time control and monitoring and virtual reality and 3D animation. The most interesting and attractive aspect of this three-dimensional setting is the camera handling through which the user interacts with the virtual world. Figure 4 shows this issue. Figure 5 presents the RSA-2 robot V.R. PC simulation connected with the electronics control in a real time synchronic way, so the operator can see a simultaneous and rhythmic movement between the 3D PC screen and the real robot.

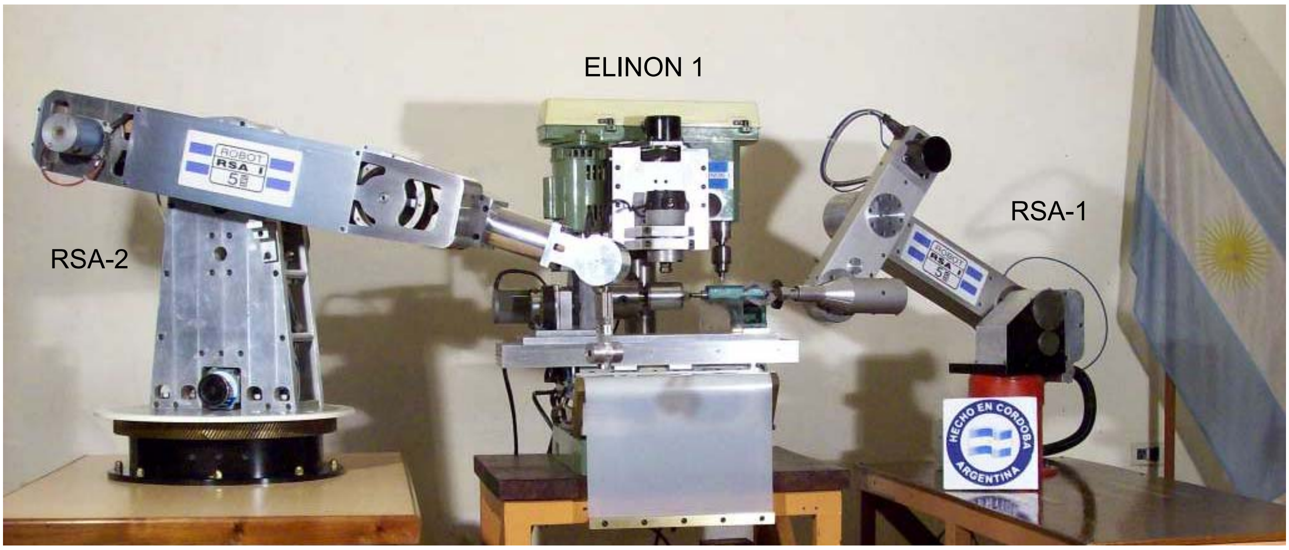


Figure 1. Flexible manufacturing cell *“Celflex”*

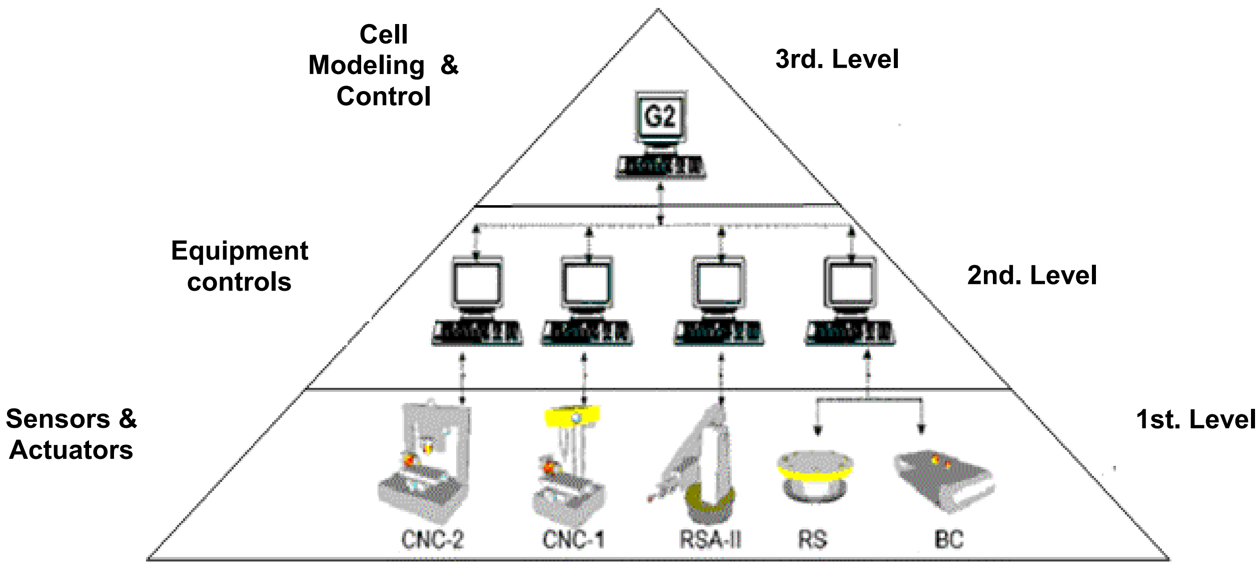


Figure 2. Cell pyramid hierarchical simulation and control

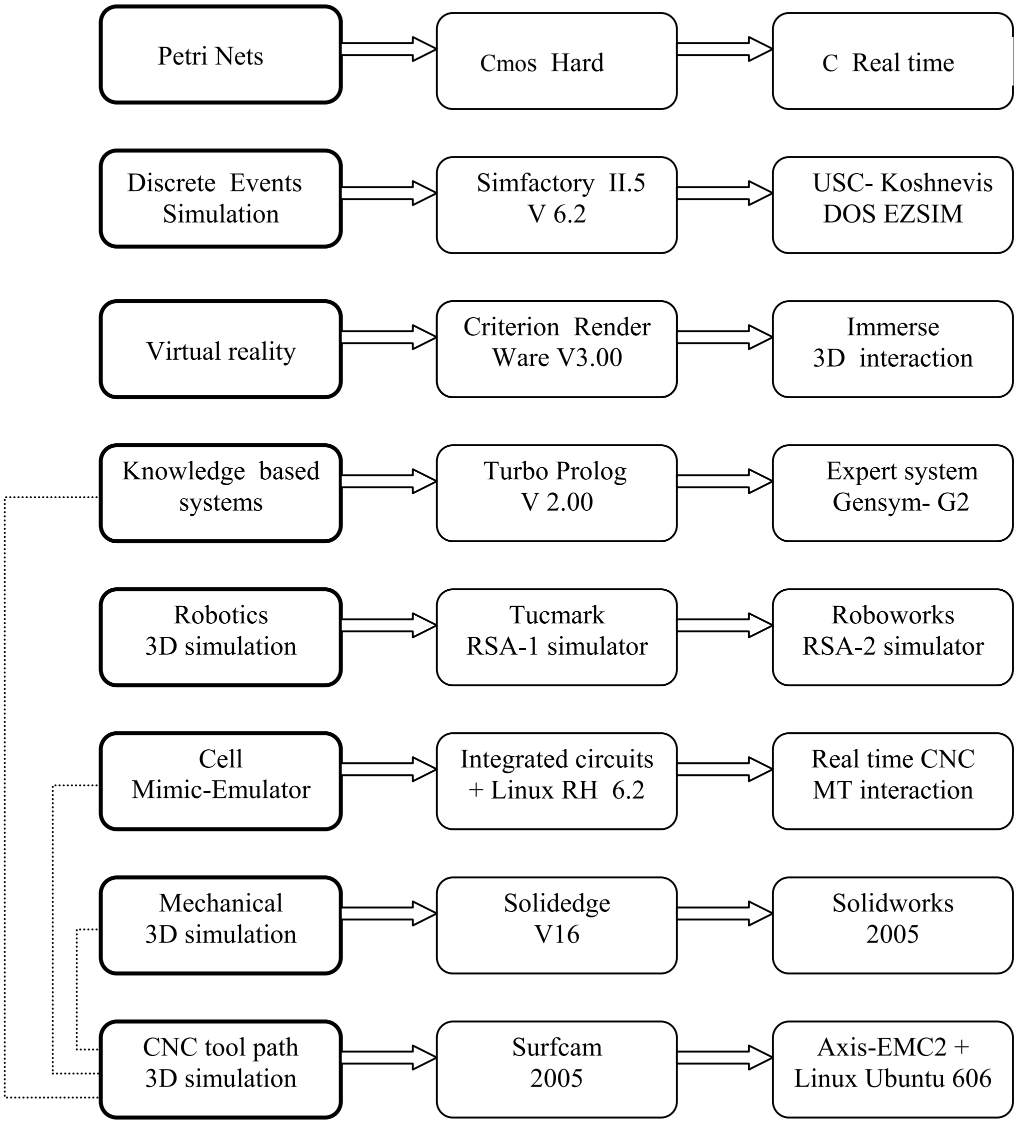


Figure 3. Overview of the manufacturing modeling and simulation methodology

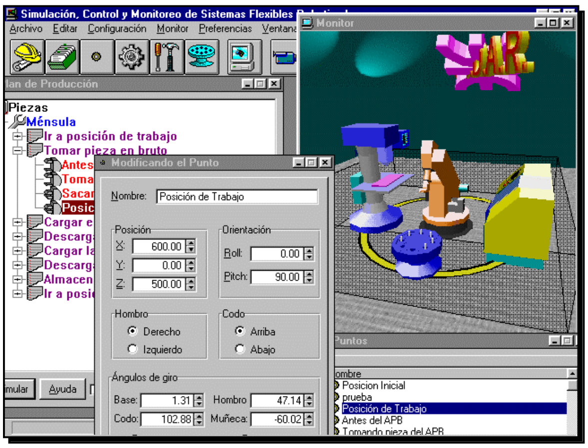


Figure 4. *"Celflex"* virtual reality (V.R.) simulation

Figure 5. RSA-2 robot V.R. simulation

The other trial was to develop a robot 3D simulator . Artola (1999) designed a simulation program written in C intended for the tutorial robot RSA-1. Apóstoli et al (2007) have been developed the RSA-2 experimental robot simulator built around the "Roboworks " , a kit from the Robotics Research Group, University of Texas-Austin. U.S.A.

2.1 Expert system modeling

Following the ground theoretical bases on Artificial Intelligence (A.I.) bibliograghy laid by Nillson (1987), Wiston (1992), Rich and Knight (1991) and Gevarter (1985) and searching for expert systems (ES) principles explained mainly by Gonzalez (1993), López (1988), Giarrataro (2000) , Avello (1993), and Kusiak (1990), the project leader (PL) decided to acquire the G2 Gensym ES. It is a comprehensive, integrated hybrid object-oriented environment shell. So the team could be able to apply knowledge to the cell operation data in order to reach conclusions, execute decisions and provide advice to other researchers, designers and operators of manufacturing systems. The G2 objects are a powerful and intuitive way to represent the physical equipments and abstract aspects of the cell applications. Any object or group of objects can be copy repeatedly. Objects, rules and procedures can be grouped into library modules that are shared by all G2 cell applications. Expert knowledge is expressed using G2 rules, which work in real time and can mimic the human experience-ability to focus on specific manufacturing problems while maintaining a general awareness. Rules can be event-driven (through forward chaining) to automatically respond whenever new data arrives. Procedures in G2 work in real time and can be schedule to milliseconds for continuous operation. Applications can process thousands of rules per second and concurrently execute rules, procedures, and models based on defined priorities.

The expert modeling and simulation project was integrated by the PL as a unit with 3 subprojects: 1) the Model conducted by Tamagnini (2004), 2) the Mimic-Emulator carried out by Trod (2004) and 3) the Real Time Interface G2-GSI built by Gonzalez (2005). Each of these three subprojects belongs to the Final Project dissertation for obtaining the Electronics Engineering degree at the National University of Cordoba.
Tamagnini started with the ground bases of G2 and later on developed the specific "Celflex" modeling application shown in fig. 6. It describes these five following areas:

a) the *workspace* which laid the equipment objects, such as the robot ROBOT-1, the computer numerical control machine tool (CNC MT) CNC-1, the CNC MT CNC-2, the rotating 8 workpieces (WP) storage RS-1, the belt conveyor WP transporter BC-1, and the operator who supplies (by hand) the raw material to the RS-1. We can see the dynamic movement of WP 2, 4, 5 and 8 around the ROBOT-1, BC-1 and CNC-1.

b) the *logic states* presenting the status of robot, the two CNC MT and the two storages, in this case the robot transporting the finished WP 8 to the BC-1, and the CNC-1 working on the WP 5.

c) the *workpieces production* reflecting the 3 jobs WP conditions : incomplete, processing and complete. The screen shows the complete work pieces WP2 and WP4 (both located at the BC-1) and the complete WP8 (at the robot RSA-1 gripper). The WP5 is in processing at the CNC MT CNC-1.

d) the *message board* presenting the log about some actions that are taking , e.g. the robot ROBOT-1 transporting WP8 towards the BC-1, as was described early at the workspace area.

e) the *resources timing* log drawing the transient time responses of CNC MT CNC-1 & CNC-2 and the robot ROBOT-1. The 3 graphics reflect the idle, busy, waiting–unload and working conditions for the CNC MT, and the idle, busy, searching and transportation monitoring of ROBOT-1.

With this working model, the G2 ES can help us to optimize the cell operating efficiencies and tuning up the resources throughput. The objective is to lower the production time as much as possible, analyzing the processing and the idle times of each CNC MT and the robot .The rule heuristic embraces this paradigm:

> *If there is some CNC MT idle, and there are more than one WP in the WP queue, and the first WP in the WP queue requires a CNC MT that is now working in a processing way, then search some WP in the queue for sending it to other idle CNC MT.*

Appling these criteria, four optimizing rules named ESC4.A/B/C/D, were written. Figure 7 presents the encircled texts including the procedure called *optimizar-uso-cnc* started by the four rules, which also inform the operator the rules fired with the brackets: (and inform the operator that "dispara 4.a/b/c/d"). In an optimized flexible manufacturing cell model, the raw pieces and the CNC programs would be set in a random way, according to the manufacturing scheduling designed in an integrated CAD/CAM site. Table 1 presents, as an example , a test case of production: a 8 pieces batch with the 4 optimized rules applied (batch 8) and not applied (batch 7). In this case the random WP sequence is 26381574 and gave this improving results:

Production time: 21% less than without rules applied.
Robot–1 working time: 6.73 % more.
Machine tool CNC-1 working time:4.95 % more.
Machine tool CNC-2 working time:13.47 % more.
Machine tool CNC-1 waiting time: 3.83 % less
Machine tool CNC-2 waiting time: 5.33 % more.

This expert model could demonstrate its capabilities searching the best cell layout arrangement for better management of its complex and time-critical operations. Even more, through the Praehofer (1994) "timing windows" algorithm, it could analyze some out of service machines and dangerous conditions, so it brings a fault tolerance environment in order not to stop the production. Trod designed and built a mimic-emulator device for representing the cell equipment behavior , instead of connecting the real CNC machines and robots directly to the G2 workstation. A designer-operator can simulate each cell component moving (by hand) toggle and rotating switches so the emulator can read the electronic sensors situation. At the beginning, the G2 model and the mimic were stand alone devices. Following the Sommerville´s advices (2002), Gonzalez (2005) designed and made a bridge connection between the G2 Unix platform and the Linux Red Hat 6.2 operation system, making it with a G2 subset called Gensym Standard Interface (GSI) through the physical link Ethernet 10 Base 2 and developing TCP/IP socket modules running under an innovative structured protocol called Celflex Communication Protocol (CCP). Figure 8 displays the G2-GSI-Mimic integration. At lab, we connected the ELINON 1-Linux Enhanced Motion Control (EMC, from the National Institute of Standard and Technology NIST-U.S.A.) with the expert system, so the integrated system could simulate and move 3 axes; with a real time high 8 mm. video camera monitoring the machine. It was necessary because the two CNC machines and the two robots are located at the ground floor and the Unix V3.2 Workstation and the mimic with the Linux PC are in the 1st. floor. We could filled in the level gaps appeared at the pyramid hierarchical structure presented in fig.2. This is an innovative applied research project, because the team joined and could run *working* altogether: the expert model, the simulator and the CNC Linux EMC control bringing an advanced manufacturing site. Now, the group is testing a new EMC called EMC2 (2007) running on a PC Intel mother board D946GZIS , 1 GB Ram, Core 2 duo E6320 processor at 1.86 Ghz , 1066 MHz. FSB, 4 MB L2 cache. This PC has two hard disks for dual booting: one for running the Windows XP O.S., and the other one for Linux Realtime CNC Ubuntu 6.06 LTS (2006). Its target is to control the new Elinon 5 axes CNC machine tool.

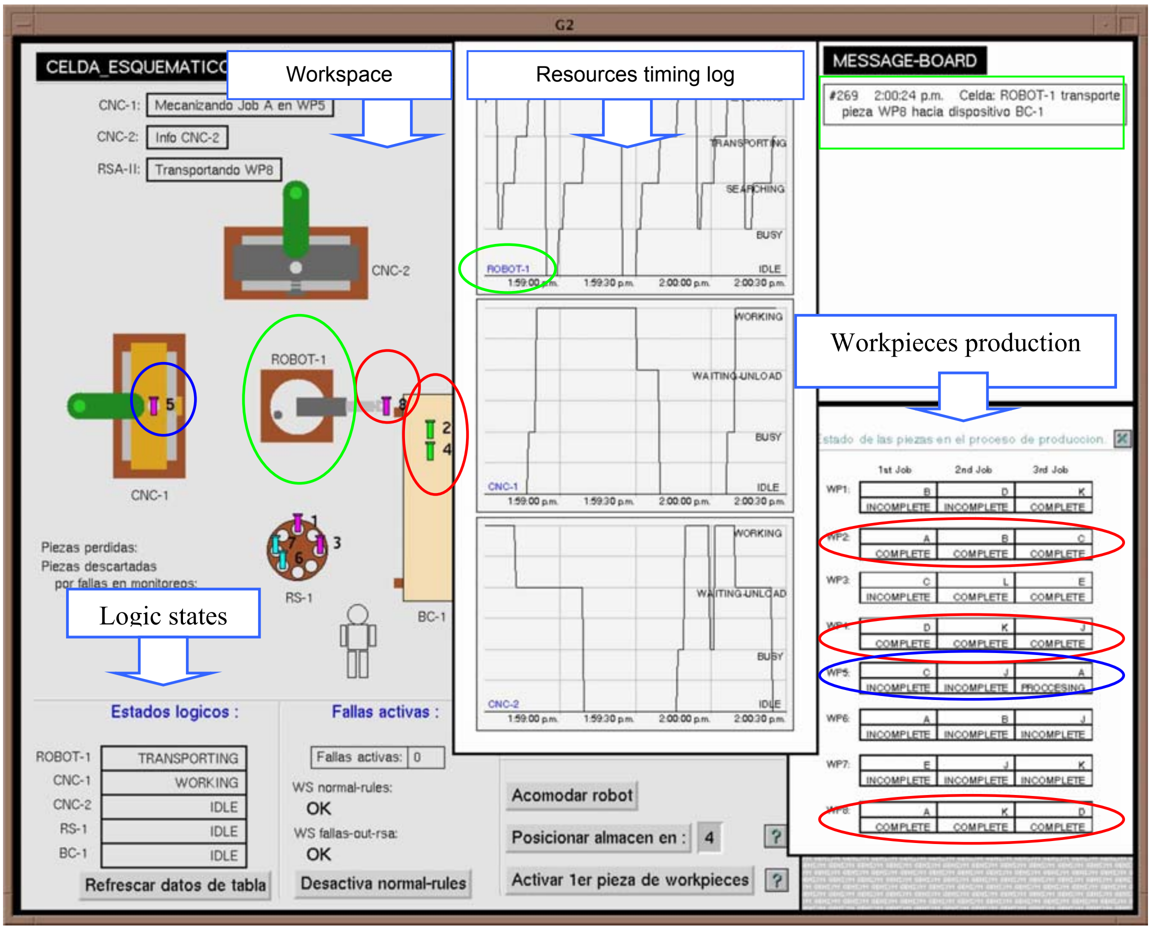
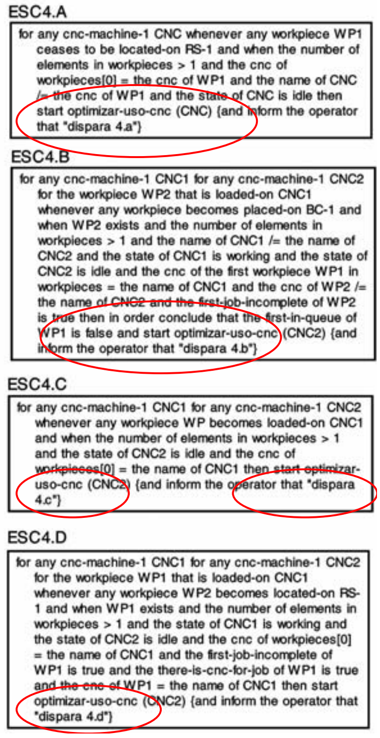


Figure 6. G2 expert modeling of the experimental lab manufacturing *"Cellflex"*

Measure	Batch 7 *No optim.*	Batch 8 *Optimized*	Impr.
Production time (sec.)	813	642	-171 (-21%)
POC in ROBOT-1	68.93	75.66	6.73 %
POC in CNC-1	45.75	50.70	4.95 %
PWAIT in CNC-1	13.81	9.98	-3.83 %
POC in CNC-2	24.91	38.38	13.17 %
PWAIT in CNC-2	14.8	20.13	5.33 %

Table 1. Expert system cell manufacturing optimization



ESC4.A

for any cnc-machine-1 CNC whenever any workpiece WP1 ceases to be located-on RS-1 and when the number of elements in workpieces > 1 and the cnc of workpieces[0] = the cnc of WP1 and the name of CNC /= the cnc of WP1 and the state of CNC is idle then start optimizar-uso-cnc (CNC) {and inform the operator that "dispara 4.a"}

ESC4.B

for any cnc-machine-1 CNC1 for any cnc-machine-1 CNC2 for the workpiece WP2 that is loaded-on CNC1 whenever any workpiece becomes placed-on BC-1 and when WP2 exists and the number of elements in workpieces > 1 and the name of CNC1 /= the name of CNC2 and the state of CNC1 is working and the state of CNC2 is idle and the cnc of the first workpiece WP1 in workpieces = the name of CNC1 and the cnc of WP2 /= the name of CNC2 and the first-job-incomplete of WP2 is true then in order conclude that the first-in-queue of WP1 is false and start optimizar-uso-cnc (CNC2) {and inform the operator that "dispara 4.b"}

ESC4.C

for any cnc-machine-1 CNC1 for any cnc-machine-1 CNC2 whenever any workpiece WP becomes loaded-on CNC1 and when the number of elements in workpieces > 1 and the state of CNC2 is idle and the cnc of workpieces[0] = the name of CNC1 then start optimizar-uso-cnc (CNC2) {and inform the operator that "dispara 4.c"}

ESC4.D

for any cnc-machine-1 CNC1 for any cnc-machine-1 CNC2 for the workpiece WP1 that is loaded-on CNC1 whenever any workpiece WP2 becomes located-on RS-1 and when WP1 exists and the number of elements in workpieces > 1 and the state of CNC1 is working and the state of CNC2 is idle and the cnc of workpieces[0] = the name of CNC1 and the first-job-incomplete of WP1 is true and the there-is-cnc-for-job of WP1 is true and the cnc of WP1 = the name of CNC1 then start optimizar-uso-cnc (CNC2) {and inform the operator that "dispara 4.d"}

Figure 7. Expert rules applied

Figure 8 G2-GSI-EMULATOR integration

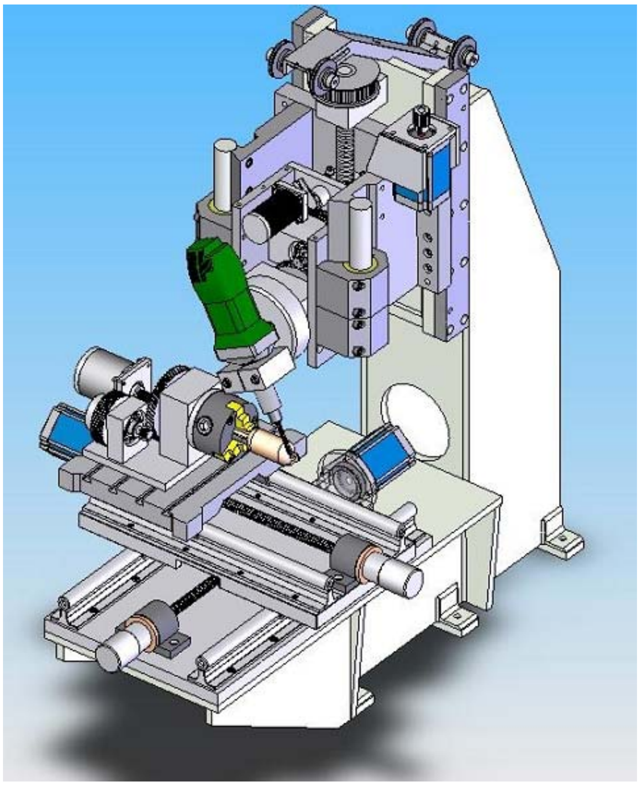
2.2 Mechanical representation & simulation

In Córdoba city there are several 5 axes CNC MT among others, can be mentioned: two Jobs-Jomach series 24x (from Italy) that are manufacturing molds and dies, two Droop & Rein gantry type (Germany) and one Fidia series G99x (Italy) for aeronautical production, and a Mori Seiki series NMV5xxx (Japan) for tool makers. As was explained before, the group is carrying out the whole design and construction of the 5 axes CNC MT named ELINON 2. It is an advanced project with the most native added value. Actually, most of the parts are built and assembled. But a small enterprise I.P. (2006) required a facility study in order to manufacture a new mold for its medical vessel (a plastic sachet) with this 5 axes machine. Because of the machine is not yet completed, a 3D simulation was a mandatory solution. The first step was to pour the AutoCad (2005 IGES files) part drawing to Solidworks (2005). Some parts have been designed directly inside this 3D Cad.

After several months of continuous effort, Lopez and Boock (2006) presented the simulation environment. Figure 9 exhibits a 3D simulation of the 5 axes machine with the tool manufacturing the vessel mold. Moreover, it is possible to see the 3D dynamic movement (in Quick Time) at several velocities, resembling a movie taken by a video camera. This is a good contribution, and the designer can look ahead the project overview avoiding dangerous collisions and to verify: a) the proper transverses and rotating span axes, b) the limit and home switches axes positions, c) the tool length and diameter , and d) the effective part manufacturing volume capacity. So, the design can be quickly optimized allowing to reach low scratch part units, reducing the whole budget and shorting the delivery dead time. Apóstoli (2006, 2007) reported some lab results concerning with the 4th and 5th rotation axes. Conforto (2006) designed with Solidedge V16 Cad system a fuel pump 3D drawing representation with size dimensions taken from the real one.

In a Cad /Cam site the real integration is the core of the manufacturing objective. Once the 3D part design and the simulation are completed, it is mandatory to transfer the data to a CNC program. For example, figure 10 exhibits a 3D CNC tool simulation on the Linux Ubuntu 6.06 + EMC2 CNC control.

Laffaille (2006) has taken the UTN university icon Solidworks drawing and later on transferred it to the SurfCam 2005-Windows XP program which can select all the CNC parameters involved in the icon manufacturing : axes velocities and accelerations, cutting feed rates, tool and part materials, among others. The program can simulate the 3D tool movements at different speed rates, verifying the cutting shape and generating at the same time the G codes. These G codes are later saved in the ELINON 1 TurboCNC 4.01 program, which is now running on a PII 400 MHz. Windows/DOS PC linked to the Windows XP through an Ethernet 10 Base 2. Figure 11 shows the UTN icon SurfCam simulation .



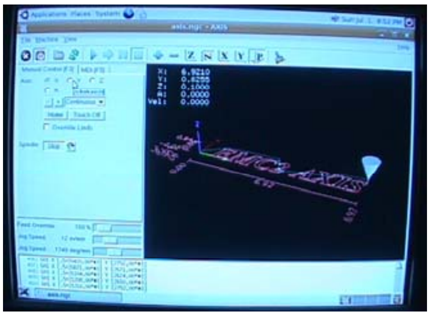


Figure 10. Linux Ubuntu 3D CNC tool path simulation

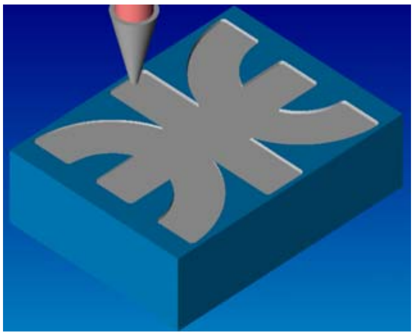


Figure 9. Elinon 5 axes Solidworks 3D simulation and animation

Figure 11.SurfCam 3D CNC tool path simulation

3. CONCLUSIONS

The modeling and simulation tools are the *first step* in an overall project. It is necessary, and constitutes the solid theoretical ground base for analyzing the "what if " scenarios and learning some experiences before to go to the real application. The *second step* is to transfer the mathematical-computational simulation algorithms into *a real* implementation concerning with "mechatronics " engineering disciplines. The final target is to reach a ***running** and* ***working*** project, and here it is possible to find out a deep gap to fill in, for coming to the reality. The team discovered the manpower resources and some handcraft abilities for constructing the final working model and, of course, the group realizes that at this point it is very important the background life experiences acquired in a real practical world. So, this manufacturing project is an *integrated* activity from the top (modeling and simulation) to the bottom (practical equipment implementation). Figure 2 unveils this concept. Closing the strategic triangle: research, university and S&ME enterprises, this experimental flexible manufacturing "CelFlex" embraces all the already mentioned levels and it is an innovative long term project, that the team is developing for more than 10 years.

Actually the cell is producing engraved parts with the Elinon I CNC MT and the RSA-1 robot. Once the Elinon 2 will be finished, it can manufacture complex 3D parts such as bioengineering prostheses and aerospace components. The cell is also a proper educational site for training university people: students, graduates and teachers.

It is wise to point out that the project objectives are included into the bicentennial argentine program called PROTIS ("Programa Transversal Integrado del Sistema Nacional de Innovación" ; www.secyt.gov.ar). It should be mentioned that an outstanding high quality reference related to this issue is the Brazilian National Project called IFM ("Instituto Fábrica do Milénio ") with its NUMA ("Núcleo de Manufatura Avançada") promoted by the Science and Technology Minister of Brazil. (www.ifm.org.br , www.numa.org.br, www.cnpq.org.br)

4. ACKNOWLEDGMENTS

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