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DIGITAL FACTORY SIMULATION TOOLS FOR THE ANALYSIS OF A ROBOTIC MANUFACTURING CELL

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ABSTRACT

Modern manufacturing systems need continuous improvement in order to meet the rapidly changing market requirements. A new concept in the field of production engineering has been conceived to optimize manufacturing systems design and reconfiguration: the Digital Factory. This approach is based on the integration of diverse digital methodologies and tools, including production data management systems and simulation technologies. In this paper, the Digital Factory approach is applied to the analysis of an existing manufacturing system dedicated to aircraft engine components production. Different manufacturing cell configurations involving the employment of handling robots are studied through integration of modelling and simulation activities carried out by means of both Discrete Event Simulation (DES) and 3D motion simulation software tools.

KEYWORDS

Digital Factory, Manufacturing Systems, Discrete Event Simulation, 3D Simulation

1. INTRODUCTION

Today's manufacturing industry is characterised by a very dynamic environment, pushing at frequent reconfiguration and improvement of manufacturing systems. One of the main requirements of current manufacturing systems is the so-called 'responsiveness' to external drivers such as market demands, that enables rapid launch of new products, fast adjustment of system capacity and functionality, and easy integration of new technologies into existing systems (Tolio et al, 2010).

Manufacturing system design and reconfiguration require to examine as often as possible a number of alternative solutions. Analytical methods, both static and dynamic, have been proposed in literature and are often used to calculate performance measures of alternative solutions (Gershwin, 1994; Matta et al, 2005; Li and Meerkov, 2009). However, applied to the analysis of modern complex manufacturing systems, such methods can be very complicated and time-consuming.

For this reason, design and reconfiguration can be effectively supported by the employment of Information Technology (IT) (Westkämper, 2007; Maropoulos, 2003). In recent years, the evolution of IT has encouraged a significant introduction of new digital technologies in manufacturing (Chryssolouris et al, 2008).

In this framework, the Digital Factory concept has been introduced as a new paradigm in which production data management systems and simulation technologies are jointly used to optimize manufacturing system design and reconfiguration (Bracht and Masurat, 2005; Gregor et al, 2009; Schloegl, 2005; Woern et al, 2000). The key factor is the integration of the various processes and activities by using common data for all the applications (Kuhn, 2006).

The employment of digital modelling and simulation tools can reduce time and cost in the design of complex manufacturing systems, avoiding hard analysis and experimentation (De Vin et al, 2004; Papakostas et al, 2011).

Simulation has a primary role and different purposes on the basis of the simulation software tool employed (Hosseinpour and Hajihosseini, 2009).

Discrete Event Simulation (DES) is a valuable tool for experimenting with different manufacturing system "what if" scenarios, allowing to investigate the system performance in terms of production flow, bottlenecks, productivity, etc. (Caggiano et al, 2009). On the other hand, 3D motion simulation can be conveniently adopted to examine manufacturing system layout, ergonomics, and robotics issues (Ramirez Cerda, 1995; Caggiano and Teti, 2010).

In this paper, the Digital Factory approach is applied to the analysis of two actual manufacturing cells dedicated to the production of aircraft engine products.

Different manufacturing cell configurations involving the employment of a handling robot are studied through integration of modelling and simulation activities carried out by means of both DES and 3D simulation software tools.

3D motion simulation is employed to perform a detailed design of the manufacturing cells and assess their feasibility with reference to robot motion issues, as the possibility to reach all the objectives, the safety of movements throughout the manufacturing cell and the organisation of a suitable layout.

The 3D simulation results concerning layout modifications, equipments arrangement, estimated robot loading/unloading and processing times are used to set up the DES models of the various manufacturing cell configurations. The DES software tool is employed in order to analyse, for each system configuration, its behaviour in terms of production flow, productivity, utilization of available facilities, system bottlenecks, and so on.

The DES results are then examined in order to compare the diverse manufacturing cell configurations, with the aim to support the decision making process related to cell optimisation. The research work shows the essential role of data integration among different tools in order to carry out an accurate and comprehensive analysis of a manufacturing system, since in most cases a single simulation tool is not sufficient to take into account all the relevant issues of the design or reconfiguration tasks, in agreement with the Digital Factory concept.

2. INDUSTRIAL CASE STUDY

The Digital Factory approach has been employed in this research work to carry out investigations on a real industrial case study.

The manufacturing system under examination, dedicated to turbine vanes production, belongs to the facilities of an aircraft engine manufacturing company. Two grinding phases together with air cleaning, deburring, washing and precision measuring operations are required for product completion. Two parallel manufacturing cells, provided with the same grinding machine model, are available in the plant and they can perform similar operations on various turbine vane part numbers.

In each of the two manufacturing cells, a human operator places every vane on its proper fixture (different for each grinding phase), moves the part-fixture assembly to the various machines and performs the manual deburring of vanes.

Since manual loading of the vane-fixture assembly inside the grinding machine is a very time-consuming operation (it can take up to 15 min), the company has provided one of the two identical grinding machines with a small robot dedicated to loading and unloading of parts and fixtures on and off the grinding machine. This solution decreased the loading time from 15 to 3 min, thus reducing the 80% of its duration.

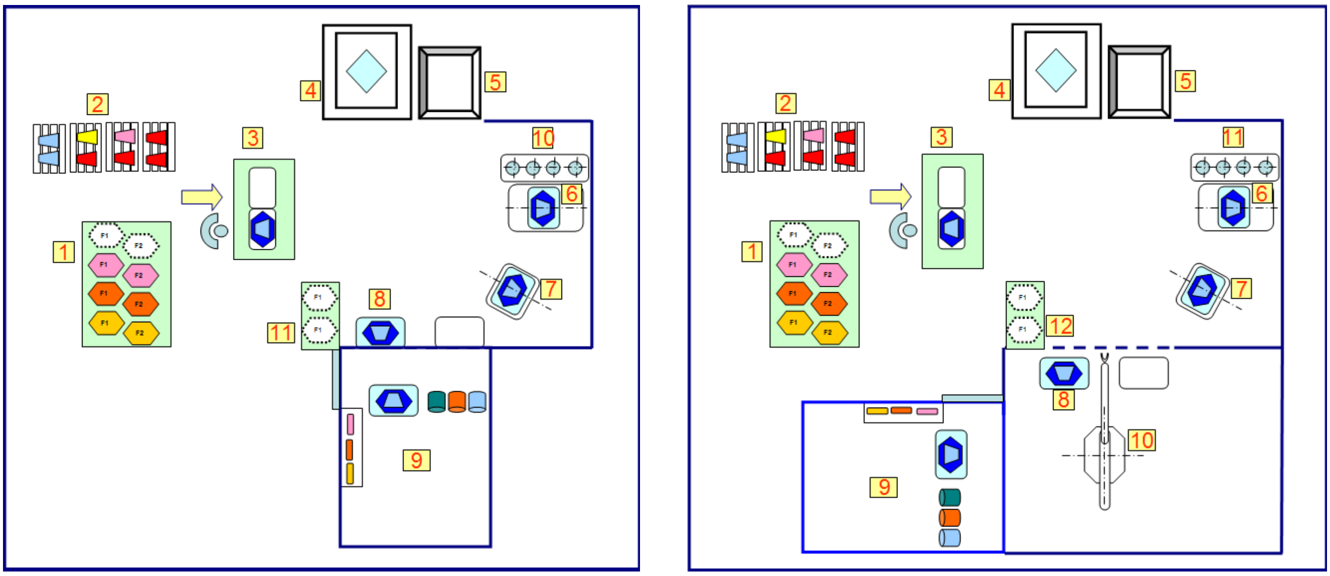
At present, two distinct manufacturing cells are available for turbine vanes grinding: one with a loading/unloading robot integrated in the grinding machine and one without it that needs manual loading/unloading. The schemes of the current cells are shown in Figure-1 a-b, while their components are summarised in Table-1.

Both cells have a deburring station where the human operator performs manual deburring on each vane after the grinding and the air cleaning phases.

This is a critical operation, since it is largely dependent on the operator's experience, manual ability and attention. An incorrect deburring process or even sporadic errors due to drop of operator concentration can produce severe damages to the part. These damages cannot be eliminated through repair machining and the vane must be rejected.

In order to reduce such risks, the introduction of a robot to automate the deburring process and avoid human mistakes has been envisaged. The same robot could be also employed to move part-fixture assemblies among the various machines, thus leaving to the human operator the only task of placing parts on fixtures.

To decide in which of the two available manufacturing cells the new robot should be introduced, the employment of simulation tools represents a very valuable support. These tools can be utilized to verify the feasibility of the robot employment in terms of layout and robotics issues as well as to examine the consequences of the introduced changes on the manufacturing system productivity.



(a) (b)

Figure 1 - Schemes of the current cells: (a) without loading robot (b) with loading robot.

Table 1. Cells components: (a) without loading robot (b) with loading robot.

N.	Manufacturing Cell Component
1.	Fixtures Buffer
2.	Input/Output Vanes Buffer
3.	Vane/Fixture Assembly Bench
4.	Coordinate Measuring Machine
5.	Washing Station
6.	Automatic Deburring Station
7.	Air Cleaning Station
8.	Grinding Input/Output Buffers
9.	Grinding Machine
10.	Tool Storage
11.	Intermediate Buffer
-	-

(a)

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9.	Grinding Machine
10.	Loading/Unloading Robot
11.	Tool Storage
12.	Intermediate Buffer

(b)

3. MANUFACTURING CELL SIMULATION

3.1. 3D SIMULATION

The introduction of a robot as new material handling system requires a deep analysis to investigate the solution feasibility in terms of reachability of all targets, safety of movements and layout reconfiguration.

This study can be carried out through the employment of 3D motion simulation tools. The latter can be suitably engaged in the design of a material handling system, such as a robot, to verify material handling layout and path as well as the integration with other handling systems, equipments and operators (Kuhn, 2006). Kinematics modules can manage computation for robot kinematics, while collision detection modules can sense collisions among hitting surfaces.

Geometrical and functional features of machines, equipments, and material handling systems are particularly relevant in this type of simulation. Models can be created on the basis of available libraries, through design within the software environment, or by importing already existing CAD files. For this simulation activity, 3D models of the components of both manufacturing cells were created, while the already available CAD files of parts and fixtures were imported.

As regards the robot models, dedicated libraries offered by the simulation software were employed to retrieve the already existing loading/unloading robot model as well as to select and test the most appropriate model for the new handling/deburring robot.

On the basis of the schemes shown in Figure-1 a-b, all the components of the two manufacturing cells were arranged in the 3D simulation software to set up the global layout with properly sized machines and devices (Figure-3 and Figure-4).

For layout optimization, particular attention must be paid to safety in order to avoid any interference between the robot movement and the other cell components as well as the human operator. Moreover, the accessibility constraints related to the robot must be taken into account to appropriately locate the components of the manufacturing cell and set their relative distances.

In this perspective, the employment of 3D simulation proves essential to virtually verify the activities that the robot has to perform in the manufacturing cell, and to determine whether the current layout allows to execute all the tasks, both in terms of reachability and safety against possible collisions.

A purpose of this simulation is to determine the type of robot that should be employed as well as the proper location of the robot that depends on its size and the need to reach all the targets, in particular the deburring station where the robot will perform the automatic deburring process. By creating target points in the 3D simulation software, it is possible to check whether a robot is able to reach all the targets with the current layout and modify the cell configuration if this condition is not satisfied.

As regards the selection of the most suitable robot model for the manufacturing cells, several factors were considered: first, the payload that should be carried and the robot size. Since the vane-fixture assemblies weigh about 15 kg, to which the gripper weight should be added, the 20 Kg robot category robot was considered too risky and the immediately subsequent 50 Kg robot category was chosen.

Another parameter to be considered is the robot dimension, since it should be able to reach all the desired targets within the manufacturing cell.

Finally, a very good accuracy is required in order to perform an acceptable deburring of products.

On the basis of these criteria, the robot chosen for handling and deburring tasks in the manufacturing cell is the FANUC M710iC/50. It has 6 degrees of freedom and can perform handling, loading and unloading of medium loads (payload is about 50 kg). The maximum reach is 2050 mm and the weight is 560 kg; its repeatability is < ±0.07 mm.

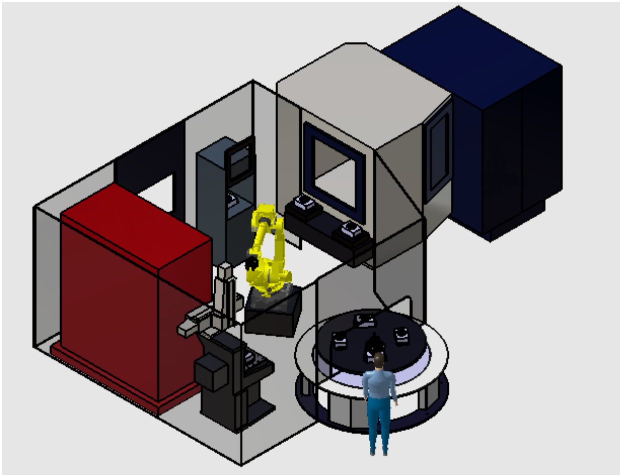


Figure 3. 3D model of the manufacturing cell with the new handling/deburring robot for 3D motion simulation.

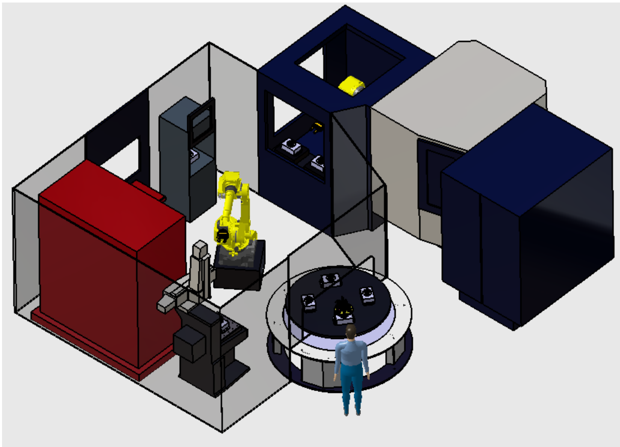


Figure 4. 3D model of the manufacturing cell with both the existing loading/unloading robot and the new handling/deburring robot for 3D motion simulation.

A 3D model of the FANUC M710iC/50 robot provided with the proper kinematics was obtained from the software robot data base.

A gripper for the robot, similar to a fork, was designed by the company engineers to handle the fixtures by inserting its prongs into the two grooves of the fixture base. The movement required to download a fixture-part assembly from a machine consists of a horizontal translation to insert the prongs into the grooves and a vertical movement to raise the assembly.

In order to take into account operation safety requirements in the manufacturing cell, not only the event of collisions between robot and machines should be considered, but also any inconvenience related to the human-robot interaction due to the presence of a human operator assembling vanes and fixtures on the assembly table.

A possible solution consists in bounding with a barrier the entire manufacturing cell zone within which the robot is free to move.

The simulation helped identifying the zones where communication with the external environment needs to be allowed.

In particular, the assembly bench was configured as a rotating table provided with input and output positions: once the labour has mounted the part on the fixture outside the cell, the part-fixture assembly enters the bounded zone automatically, allowing the operator to use a working position distinct from the robot area. A slot was designed in the barrier with a height sufficient to allow the transfer of the part-fixture assembly.

All the stations not having to be reached by the labour were located inside the manufacturing cell boundaries. As regards the grinding machines, the robot should be able to load the part-fixture assembly onto them, while the labour needs to access the tool storage area on the grinding machine side for tool change and maintenance. Thus, the safety barrier was placed in line with the front of each grinding machine.

With the described layout configurations, shown in Figure-3 and Figure-4, the simulation of robot movement throughout the cell was carried out to investigate the feasibility of the whole manufacturing cycle.

A cycle was simulated to verify the possibility for the robot to reach each single target, to examine the path followed by the robot from one target to the next, and to check if any collision occurred during the robot motion.

The robot model proved to be suitable for the manufacturing cell, as it was able to reach all the targets by suitably arranging all the manufacturing cell components.

The results of this simulation offered information on the proper layout to be adopted as well as on the robot movement and loading/unloading times.

Once the feasibility of the robot introduction in both the existing manufacturing cells was verified through 3D simulation, a valid support tool to decide in which of the two cells the robot should be more conveniently placed is represented by Discrete Event Simulation.

3.2. DISCRETE EVENT SIMULATION

Discrete Event Simulation (DES) was employed to evaluate the effects of the robot introduction into the two manufacturing cells in terms of productivity and resource utilization.

DES models of the two existing manufacturing cells (one without any robot and the other with a loading/unloading robot) and the two new manufacturing cells (both provided with a new handling/deburring robot) were built using the 3D simulation results.

The manufacturing cells components 3D models already created for the 3D simulation were imported using the standard exchange format IGES, and arranged according to the 3D simulation final layout. Other relevant data from the 3D simulation results were the robot speed and the loading/unloading time on the cell components.

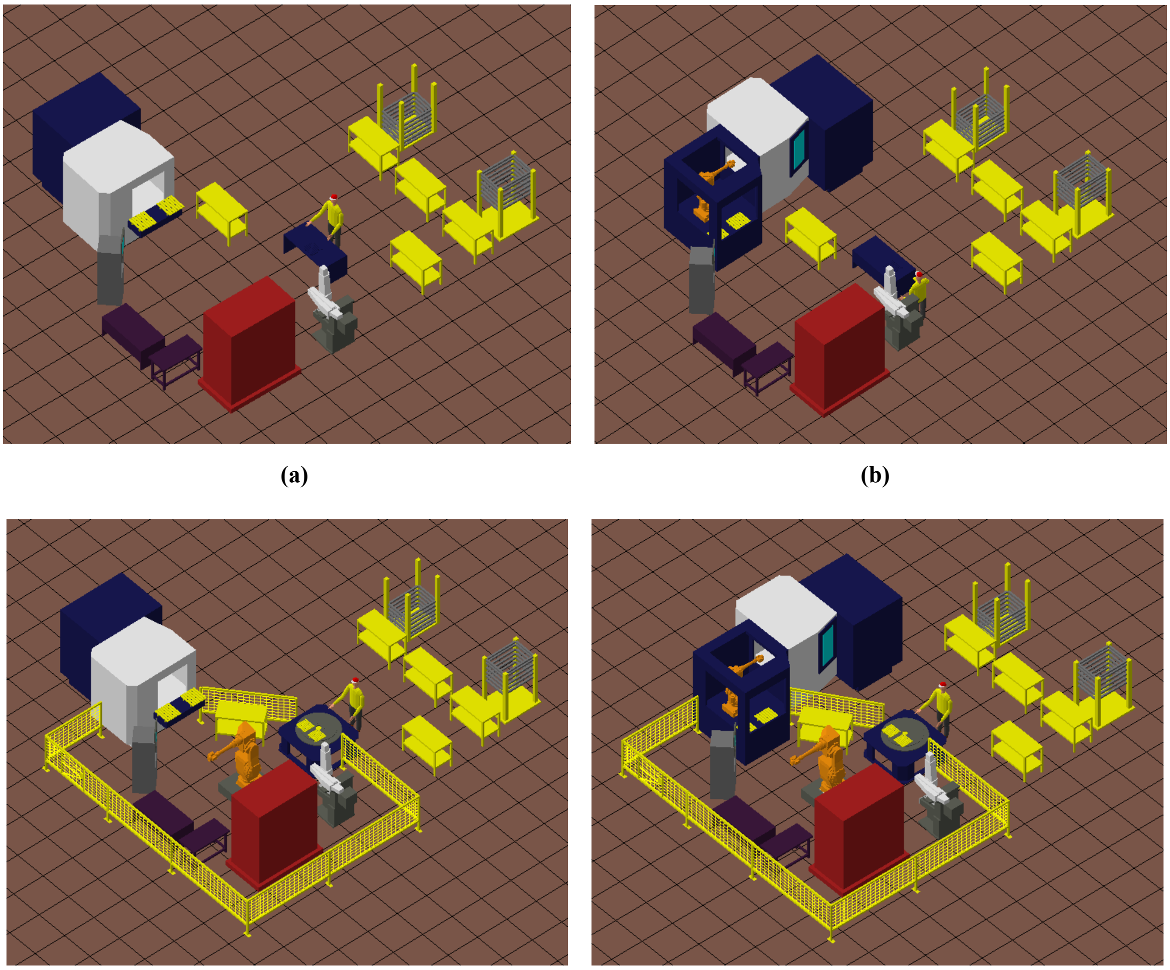
Both the existing and the new manufacturing cells were simulated, thus obtaining four simulation cases to be employed for comparison and assessment (Figure-5 a-d).

To further improve the productivity analysis, for each of the four simulation cases, the number of fixtures per phase was progressively increased to examine the influence on production time cutback.

The resulting simulation runs, consisting in the execution of the cycle to produce a full kit of vanes (34 units), showed that adding fixtures per phase is convenient only up to 4 fixtures for the cases n. 1 and n. 2, as further fixtures are not able to reduce the production time and only increase the investment cost. As regards the cases n. 3 and n. 4, 3 fixtures per phase seem to be sufficient: the production time is not affected by the addition of new fixtures that only add to the cost.

In Figure-6, for each of the four cell configurations, the total time required to produce an entire kit of vanes is plotted versus the number of fixtures per phase. It can be observed that the cell configuration showing the minimum production time is the n. 3, i.e. the one with a central handling/deburring robot. Actually, the introduction of the central handling/deburring robot in cell n. 1 yields a significant decrease of production time whereas the same robot in cell n. 2 causes only a small time reduction.

To support the decision concerning where the robot should be placed, it is useful to analyse the two possible configurations that would be created by the introduction of the robot either in cell n. 1 or in cell n. 2. In the first configuration, the central robot is introduced into the cell n. 1, thus leading to the layout of cell n. 3, while cell n. 2 remains unchanged. In the second configuration, the central robot is introduced into the cell n. 2, thus leading to the layout of cell n. 4, while cell n. 1 remains unchanged.



(a) (b)

(c) (d)

Figure 5. DES models for the four manufacturing cells arrangements:
(a) current cell without any robot (b) current cell with loading robot
(c) new cell with a central robot (d) new cell with both loading robot and central robot

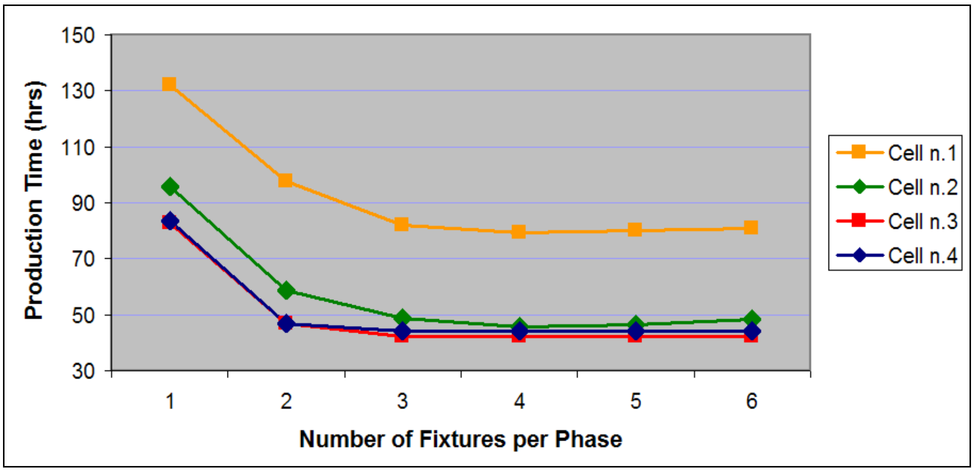


Figure 6. Production time vs. number of fixtures per phase for the 4 simulation cases.

■ **Cell n.1: cell without any robot**

◆ **Cell n.2: cell with a loading/unloading robot**

■ **Cell n.3: cell with a central handling/deburring robot**

◆ **Cell n.4: cell with both loading/unloading and handling/deburring robots**

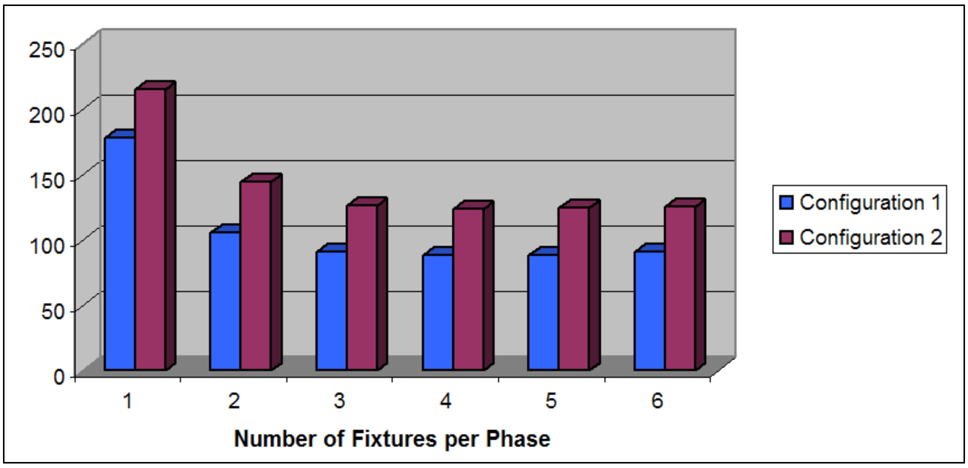


Figure 7. Production time vs. number of fixtures per phase for the two configurations.

■ Configuration 1: cell n.2 and cell n.3; ■ Configuration 2: cell n.1 and cell n.4

The production time versus the number of fixtures per phase is reported for both first and second configuration in Figure-7. The bar chart shows that the first configuration leads to shorter production times for any number of fixtures from 1 to 6. Thus, this configuration seems to be the best solution and the handling/deburring robot should be placed into cell n. 1, presently without any robot, so to optimize the production time.

As regards the number of fixtures per phase, Figure-7 shows that the minimum production time for the first configuration is reached with 4 fixtures.

However, by examining Figure-6, one further consideration can be made: the minimum production time for cell n. 2 is achieved when 4 fixtures per phase are employed, but for cell n. 3, only 3 fixtures per phase are sufficient since no improvement is verified with further fixtures.

Thus, the optimal solution in terms of both productivity and fixtures cost is given by the first configuration composed of cell n. 2 with 4 fixtures per phase and cell n. 3 with 3 fixtures per phase.

4. CONCLUSIONS

In this paper, the Digital Factory approach was applied to the analysis of a real manufacturing system dedicated to the fabrication of aircraft engine products.

Diverse manufacturing cell configurations involving the introduction of handling robots were studied through integration of modelling and simulation activities carried out by means of DES and 3D motion simulation software tools.

3D motion simulation was employed to perform a detailed design of the manufacturing cells and assess the feasibility of different cell configurations in terms of robot motion, reachability of all targets and safety of movements.

The 3D motion simulation results concerning layout, equipments arrangement, estimated robot loading/unloading and processing times were used to define the manufacturing cells DES models.

For each cell configuration, DES was employed to analyse the cell behaviour in terms of production flow, productivity, resource utilization and bottlenecks of the system. The DES results were therefore examined to compare the diverse cell configurations and their performance in terms of production time in order to support the decision making for optimal solution identification.

A single simulation tool was not sufficient to consider all the relevant issues for manufacturing system design as, in the Digital Factory framework, integration of different simulation tools is essential to reach an accurate and comprehensive analysis.

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