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Digital Factory Concept Implementation for Flexible and Reconfigurable Manufacturing Systems Modelling and Analysis

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Abstract

In modern manufacturing industry, the ever-changing turbulent environment as well as the strong competition among companies require manufacturing systems that are easily upgradable and into which new technologies can be readily integrated. Indispensable requirements for modern flexible and reconfigurable manufacturing systems are related to system responsiveness, that enables rapid launch of new product models, fast adjustment of the manufacturing system capacity to market demands, easy integration of new functions and process technologies into existing systems, and easy adaptation to variable quantities of products.

However, modern technology development has made the manufacturing environment so complex that a comprehensive planning approach is needed for the design or enhancement of a manufacturing system.

In order to develop methods for rapid product and process realization, efforts are currently spent to further introduce the role of information technology (IT) in modern manufacturing systems.

On of the main areas of research is the development and implementation of integrated digital tools taking into account the reconfigurability of systems, with the aim to realise the so-called Digital Factory. According to the Digital Factory concept, production data management systems and simulation technologies are jointly used for optimizing manufacturing systems design and reconfiguration. Digital factory implementation would allow for the shortening of planning time and cost and the improvement of planning results quality.

This research activity is focused on the role of simulation in the Digital Factory approach, and the importance of data integration among different tools.

Two different categories of simulation software tools were applied to the study of a real manufacturing cell dedicated to the production of turbine vanes in a real industrial plant of the Avio SpA company. The Discrete Event Simulation software QUEST was employed in order to analyse the actual system's behaviour in terms of production flow, productivity, utilization of the available facilities, bottlenecks of the system, and throughput time. Analysis of the simulation results was carried out to suggest possible areas of improvement that could increase efficiency and productivity, and a reconfiguration of the manufacturing cell through integration of a robotic material handling system was proposed. The modifications of the manufacturing cell were first simulated through DES to analyze the behaviour of the system. In order to perform a comprehensive analysis taking into account aspects related to robot motion, as the possibility to reach all the objectives, safety of movements throughout the manufacturing cell and the configuration of a suitable layout, the 3D simulation software DELMIA V5 was additionally employed to perform a detailed design phase of the manufacturing cell. The results of this 3D simulation concerned layout modifications and the estimated robot loading/unloading and travel times, necessary to update and refine the manufacturing cell DES model and carry out a more reliable simulation of the virtual cell. For this reason, the 3D simulation generated data were integrated within the DES software, where the behaviour of the manufacturing cell could be finally analysed with reference to productivity and utilization of the available resources. The results of the new simulation could be examined in order to make a comparison with the original manufacturing cell model, with the aim to support the decision making process. The application shows the fundamental 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 in the planning or reconfiguration process. The advantages offered by the integration of the two simulations are consistent with the main idea of the Digital Factory concept, that is based on the integration and data exchange among different tools for design, engineering, planning, simulation, communication, and control.

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CHAPTER 1

INTRODUCTION

1.1 MANUFACTURING SYSTEMS AND DIGITAL FACTORY CONCEPT

Modern manufacturing environment is extremely turbulent and uncertain, due to phenomena related to market globalisation and the rapid improvements achieved in technology. Such turbulent environment as well as the strong competition force manufacturing industries to dynamically innovate, adapt and improve manufacturing systems, by reassessing their production paradigms to operate efficiently in the ever-changing environment.

Many production paradigms have been proposed in the last decades: in this research work, a review of manufacturing techniques is provided, from mass production to the more recent introduction of modern flexible and reconfigurable manufacturing systems.

Flexible Manufacturing Systems (FMS) are programmable machining system configurations which incorporate software to handle changes in work orders, production schedules, part-programs, and tooling for several families of parts. The objective is to make manufacturing of several parts families possible on the same system with shortened changeover time.

On the other hand, Reconfigurable Manufacturing Systems (RMS) are machining systems which can be created by incorporating basic process modules, both hardware and software, that can be rearranged or replaced quickly and reliably. Reconfiguration allows adding, removing, or modifying specific process capabilities, controls, software, or machine structure to adjust production capacity in response to changing market demands or technologies.

While FMS offer general flexibility, RMS provide customized flexibility for a particular part-family, and will be open-ended, so that they can be improved, upgraded, and reconfigured. The objective of an RMS is to provide exactly the functionality and capacity that is needed, when it is needed. It goes beyond the objectives of FMS by permitting reduction of lead time for the launch of new systems and the reconfiguration of existing systems, and rapid modification and quick integration of new technology and new functions into already existing systems. RMSs have a key role in modern manufacturing, since they are designed for rapid adjustment of production capacity and functionality, in response to new market conditions.

While in the past, manufacturing systems were configured once for a stable environment, in today’s turbulent environment, a permanent adaptation of the manufacturing systems is required: enterprises should overcome the old procedures and configure their organizations continuously.

However, modern technology has made the manufacturing environment so complex that a comprehensive planning approach is needed. The improvement of a manufacturing system requires the enhancement of its sub-systems or components, since it is a collection of entities which all work together for the benefit of the whole. When a change is made in any of the components, it affects the other entities and the behaviour of the system as a whole. Therefore, every enhancement of such a complex system should be designed following a systematic and comprehensive approach, with consequent difficulties and complexities concerning the analysis and evaluation of the system's performance.

In order to meet all these requisites, efforts are currently spent to further introduce the role of information technology in modern manufacturing systems. Following this direction, application of information technology in various stages of product design, production scheduling and process planning, machines control and processes monitoring (both on and off line), automation, quality control and networking and communication, and are now under deep study and are going through a rapid development. A systematic model of the planning tasks and the integration of new computerised techniques up to the high end of virtual reality can be used to realise a dynamic optimisation of production networks and specific processes.

Therefore, the Digital Factory concept has been introduced in the field of production engineering as a new approach based on the integration of diverse digital methodologies and tools. The Digital Factory can be defined as a "comprehensive network of digital models, methods, and tools, including modelling, simulation and 3D/Virtual Reality visualization, integrated by a continuous data management" (Chryssolouris et al., 2008). The aim of this set of software tools and methodologies is to comprehensively design, model, simulate, evaluate and optimize products, processes and systems before a new factory is built or any modification is actually carried out on an existing system, in order to improve quality and reduce time of planning processes (Bracht et al., 2005; Kühn, 2006). One of the main advantages of the Digital Factory is that all the aspects of a factory can be developed and improved until the physical manufacturing of a product meets the quality, time and cost requirements (Park). The Digital Factory provides solutions to design, evaluate, monitor and control an entire manufacturing system based on 3D CAD, simulation, database and computer networks.

The role of simulation is fundamental in this approach, and can have several uses on the basis of the category of the simulation software tool employed. Based on the analysis of simulation, manufacturing systems can be optimized and validated in terms of planning design, system capability, layout planning, production line balance, collision detection, planning process, etc.

As illustrated, the Digital Factory involves the use of simulation along the entire process chain, from developing of new product, planning the associated production equipment and organizing production. Therefore, it involves more than the simple use of simulation tools. All activities in the plant – that means the whole workflow - have to be standardized (Arndt, 2006). The data outcome of every step of the workflow has to be specified and the data of the workflow, when a step is finished, should be stored into a global factory wide database.

Models created for one purpose can potentially be used to provide support for other tasks. This requires that the simulation models can be fed with historical data as well as with snapshot data. Furthermore, the models must be able to communicate with other business software. Furthermore, the expanded and continuously updated models provide a good tool to study the effect of planned new product introduction in existing manufacturing systems (DeVin et al., 2004). The Digital Factory seem to be realisable by using multi-scaling (up and down) data and process models. Permanent and participative factory planning on all levels reduces the planning time and costs. The focus and key factor in this paradigm is the combination of the various planning and simulation processes by using common data for all applications. This approach would enable collaboration with the employment of virtual models for different purposes and different levels of detail.

The integration at the base of the digital factory requires powerful interfaces and database systems for the joint use of actual data and modules between different complexity levels (vertical integration) and between the operational function areas (horizontal integration).

This aspect is really important, since the success of simulation depends on the quality and actuality of the available data. At any moment, simulation must have access to the up to date data of development and planning.

The large quantities of data and the equally large number of different data formats constitute one of the main challenges associated with the digital factory.

The first major challenge connected to data consistency inside the Digital Factory is related to the heterogeneity of tools and methods, in particular between the different simulations.

The second challenge connected to data consistency inside the Digital Factory is related to the heterogeneity of models used for simulation: diverse simulation families are currently available and they employ different models containing various levels of information.

1.2 RESEARCH OBJECTIVES

This research is concerned with investigating the application of simulation to manufacturing systems analysis and reconfiguration in the framework of the Digital Factory concept.

The objectives of this research are:

- To examine the role of simulation in modern manufacturing systems design, analysis and reconfiguration
- To assess the importance of integrating information generated by different simulation tools in order to perform a comprehensive analysis of the manufacturing system under study, through the analysis of a real case study

In order to achieve the illustrated research objectives, two different categories of simulation software tools were applied to the study of a real manufacturing cell dedicated to the production of aircraft engine components (turbine vanes) in a real industrial plant. A Discrete Event Simulation (DES) software, DELMIA QUEST, was employed in order to analyse the actual system's behaviour in terms of production flow, productivity, utilization of the available facilities, bottlenecks of the system, and throughput time for the production of a full kit of products. The visual and numerical analysis of the simulation results was used as a basis to suggest possible areas of improvement that could increase efficiency and productivity, and a reconfiguration of the manufacturing cell through the integration of a robotic material handling system was proposed.

In order to verify and evaluate the possible improvements offered by the proposed solution on the manufacturing cell under study, further simulation analysis was necessary to verify the positive effects of the changes before their actual implementation. For this purpose, the proposed modifications in the manufacturing cell were first simulated through DES to analyze the production flow and the performance of a virtual model of the upgraded cell. In order to perform a comprehensive analysis taking into consideration aspects related to robot motion, as the possibility to reach all the objectives, the safety of movements throughout the manufacturing cell and the configuration of a suitable layout, the 3D simulation software DELMIA V5 was additionally employed to study the manufacturing cell.

The results of this 3D simulation concern layout modifications and the estimated robot loading/unloading and displacement times: this information is necessary in order to update and refine the manufacturing cell DES model in order to carry out a more reliable simulation of the virtual cell. For this reason, 3D simulation generated data were integrated within the DES software, where the behaviour of the manufacturing cell could be finally analysed with reference to productivity and utilization of the available resources. The refined DES model was then simulated and the results of the new simulation could be subsequently examined in order to make a comparison with the original manufacturing cell model, with the aim to support the decision making process.

CHAPTER 2

REVIEW ON MANUFACTURING SYSTEMS

2.1 INTRODUCTION

Manufacturing industry has an important role in economy. Research studies estimate that the total added value of these industries is about € 1.300 Billion in Europe (Westkaemper, 2007).

Nowadays, market globalisation, resulting in rapid and worldwide transfer of information and open markets is driving an evolutionary change in the global structure of manufacturing.

Manufacturing environment has a great impact on the performance of a manufacturing system, and the current huge changes of the manufacturing area are mainly determined by the rise of new phenomena and associated critical requirements in the global market environment:

- Migration of production and consumption of industrial products to developing regions;
- Turbulent and uncertain environment and influencing factors, so that only robust and transformable enterprises can survive;
- Global networking in engineering and global quality level manufacturing.

Manufacturing systems performance is affected by several factors, both internal and external to the factory environment. In recent studies on manufacturing systems, eight main factors have been identified (Westkamper et al., 2001), as shown in Fig. 1.

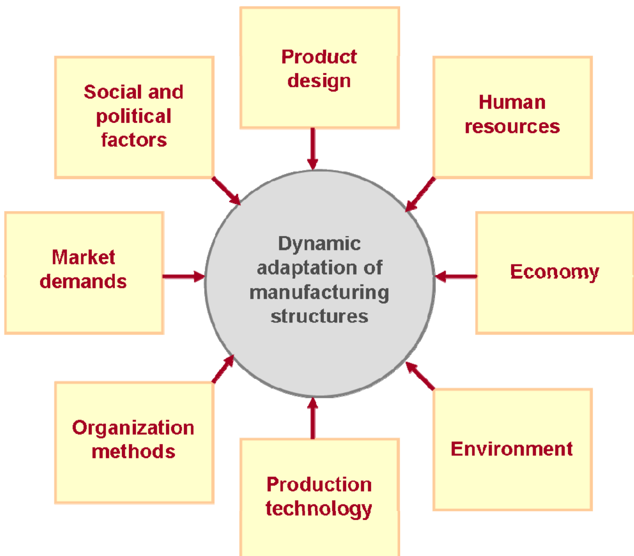

Fig. 2.1. Influencing factors in manufacturing systems.

Nowadays, practically all the identified influencing factors are permanently changing, thus affecting manufacturing performance and economic results.

While in the past, manufacturing systems were configured once for a stable environment, in today's turbulent environment, a permanent adaptation of the manufacturing systems is required: enterprises should overcome the old procedures and configure their organizations continuously.

The following objectives for future development of modern manufacturing industry have been identified (Westkaemper, 2007):

Competitiveness of European manufacturing industries
- to survive in the turbulent economic environment
- to compensate migration and consumption of technologies
- to have more and better jobs
- to stabilise economic results
- to ensure welfare and social standards of living

Leadership in manufacturing technologies
- to support innovative products and platforms
- to lead manufacturing with global standards
- to guarantee human and social standards of work

Environmental friendly products and manufacturing
- to reduce manufacturing impact on the degradation of the environment
- to substitute the consumption of limited resources
- to maximise the benefits of each product during its life cycle.

All of these targets require a strong innovation of manufacturing industries, focused on the introduction of new technologies as well as the improvement of the manufacturing systems in terms of adaptability towards the turbulent external environment. The ability to fast implement and permanently transform manufacturing structures represents a key factor to achieve success in the turbulent and uncertain current manufacturing environment.

2.2 Developments in Manufacturing Systems

Manufacturing historical roots date back to the 18th century: from then on, a number of different manufacturing paradigms have been proposed, with the aim to meet the several targets defined by the constantly changing market requirements. Research studies identify three major periods that exemplify the major changes in the focus of manufacturing processes: pre-computer numerical control, computer numerical control (CNC), and knowledge period (Mehrabi et al., 1997).

Historically, the first manufacturing paradigm introduced in the pre-CNC epoch is mass production. In mass production dedicated lines were designed for producing a specific part. This paradigm enabled the manufacturing of high volumes of one specific part type on dedicated manufacturing systems, cost-effectively and with the required quality. The core elements of the dedicated manufacturing systems are transfer lines, assembly stations, fixed tooling and dedicated automation processes. The emphasis was put on high production rates, since few product variations were required and the market was characterized by local competition.

In the CNC epoch, around the 1970s and 1980s, the emphasis on cost-effectiveness of production was enhanced together with a particular focus on product quality improvement. This trend was supported the introduction of CNC machines, as they were able to provide for more accurate manufacturing process control and then to achieve better quality products.

In this period, production paradigms developed in the Japanese manufacturing industry, became largely widespread. Among these, the known Kaizen, aimed at the continuous improvement of products and processes, the just-in-time (JIT) approach, supporting the elimination or minimization of inventory as the ideal target to reduce costs, total quality management (TQM), focused on increased and faster communications with customers in order to be able to better meet their requirements.

Another important paradigm conceived during the CNC period is lean manufacturing, developed around the 1980s, that was introduced to efficiently eliminate waste, reduce cost, and improve quality. By many (Sheridan, 1993; Noaker, 1994), lean manufacturing is considered to be an enhancement of mass production, since they have the underlying principles. In fact, it combines the features of mass production, such as high volume and low price manufacturing, with those of the so-called craft production, focused on high-quality, custom-made products. The target is the development of systems that produce finished products in response to customer demand with little or no waste. To realise this, a systemic set of principles, methods and practices aimed at reducing waste in production by reviewing all aspects of product development, manufacturing, organisation, human resources, and customer support were developed. Key lean principles are perfect first-time quality, waste minimisation by removing all activities that do not add value, continuous improvement and flexibility, Several practices are integrated into lean manufacturing: among them, the previously cited just-in-time and total quality management.

A further manufacturing paradigm is Cellular manufacturing, aimed to improve productivity with the employment of manufacturing cells. A cell is a group of workstations, machines and equipment dedicated to a process, a sub-component, or an entire product, and arranged in order to process products progressively from one workstation to another without having to wait for a batch to be completed. Usually, parts that belong to the same family advance from raw material to finished parts within a single cell. One concept behind cellular manufacturing is the so-called group technology, that consists in clustering parts into logical families with similar characteristics, so that they can be processed by the same group of machines, tooling, and people with only minor changes on procedure or set-up. In this approach, the cell units are relatively independent, each responsible for the production of a given family of products.

In a more recent time, around the 1980s, flexible manufacturing systems (FMSs) were introduced to address changes in work orders, production schedules, part programs, and tooling for the production of a family of parts. The objective of a FMS is to realise the cost-effective manufacturing of several types of parts that can change over time, with short changeover time, at the required volume and quality always on the same system, in order to simultaneously achieve productivity and flexibility. The main components of a FMS are computer numerical1y controlled (CNC) manufacturing machines, tools to operate CNC machines, robots, and automated material handling systems (MHSs). FMSs have been defined as "computer-controlled production systems capable of processing a variety of part types" (). They are based on fixed hardware and fixed, though programmable, software. In terms of design, the system possesses an integral architecture (hardware/software), i.e., the boundaries between the components and their functionalities are often difficult to identify and are tightly linked together. This type of architecture does not allow for reconfiguration changes to be made on the manufacturing system itself. Therefore, a FMS has limited capabilities for upgrading, add-ons, customization, and changes in production system.

More recently, reconfigurable manufacturing systems (RMSs) were introduced in the mid-nineties as a cost-effective response to market demands for responsiveness and customisation (Koren et al., 1997). A reconfigurable manufacturing system (RMS) is designed for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market. This type of system provides customised flexibility for a particular part fami1y, and will be open, so that it can be improved, upgraded, and reconfigured, rather than replaced. In terms of design, an RMS has a modular structure (software and hardware) that allows ease of reconfiguration as a strategy to adapt to market demands. Open-architecture control systems are one of the key enabling technologies of an RMS, and have the ability to integrate/remove new software/hardware modules without affecting the rest of the system.

Fig. 2.2 illustrates the relashionship between capacity and functionality for the main manufacturing paradigms, i.e. dedicated transfer lines, flexible manufacturing systems and reconfigurable manufacturing systems, showing the capability of RMSs to accommodate the necessary trade-offs between capacity and functionality by adapting the system itself in order change its position in the capacity-functionality space over time.

Fig. 2.3, on the other hand, shows the economic objectives of the several paradigms described above, pointing out the fact that reconfigurable manufacturing systems try to address all the objectives of the other paradigms, by adding a further objective that can be defined as responsiveness of the manufacturing process.

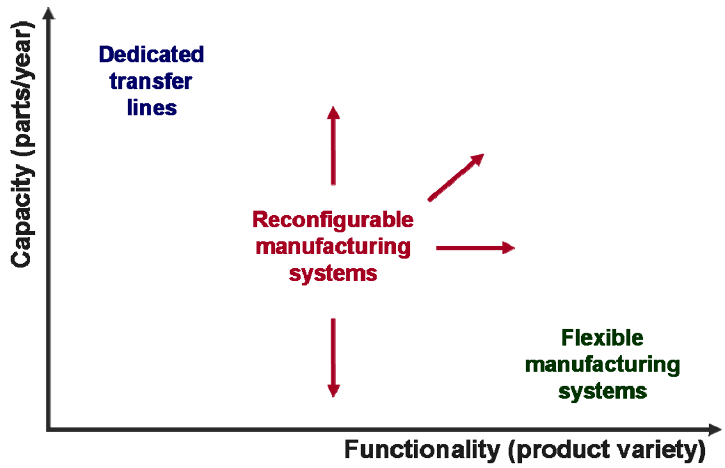

Fig. 2.2. Relationship between functionality and capacity for manufacturing paradigms.

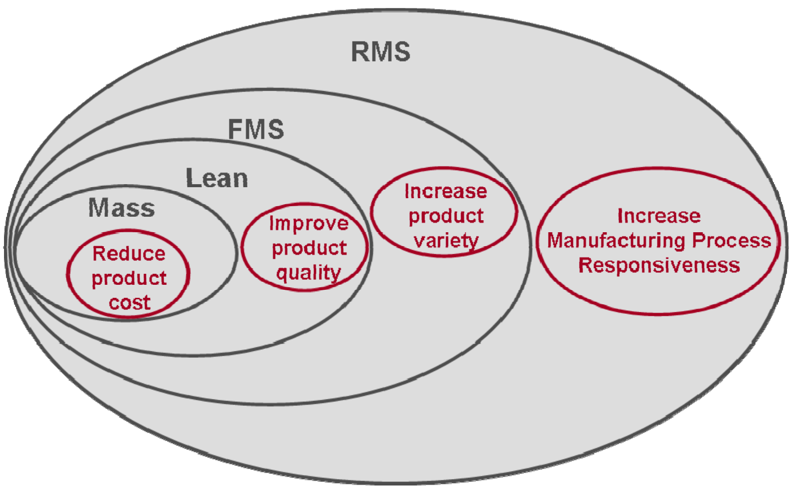

Fig. 2.3. Economic objectives of the main manufacturing paradigms.

RMSs go beyond the economic objectives of an FMS by allowing the reduction of lead time for the launch of new systems and the reconfiguration of existing systems, as well as the rapid manufacturing modification and quick integration of new technology and/or new functions into existing systems.

2.3 FLEXIBLE AND RECONFIGURABLE MANUFACTURING SYSTEMS

Some authors believe that Flexible Manufacturing Systems (FMSs) and Reconfigurable Manufacturing Systems (RMSs) are strongly overlapping, and, as the two paradigms evolve, the boundaries between them will become fuzzy whereas the complimentary and continuity features will get more evident (ElMaraghy, 2006). Since these two approaches are certainly the most relevant in modern manufacturing, they will be deeper illustrated in this paragraph, by introducing the concepts of flexibility and reconfigurability.

Flexibility can be viewed as the capacity of a system to change in response to changing requirements with little expense in terms of time, effort, cost, or performance (Toni et al., 1998).

In literature, several categories of manufacturing systems flexibility can be identified:

- *Machine flexibility*: Various operations performed without set-up change,
- *Material handling flexibility*: Number of used paths / total number of possible paths between all machines,
- *Operation Flexibility*: Number of different processing plans available for part fabrication,
- *Process Flexibility*: Set of part types that can be produced without major set-up changes, i.e. part-mix flexibility,
- *Product Flexibility*: Ease (time and cost) of introducing products into an existing product mix. It contributes to agility,
- *Routing Flexibility*: Number of feasible routes of all part types/Number of part types,
- *Volume Flexibility*: The ability to vary production volume profitably within production capacity,
- *Expansion Flexibility*: Ease (effort and cost) of augmenting capacity and/or capability, when needed, through physical changes to the system,
- *Control Program Flexibility*: The ability of a system to run virtually uninterrupted (e.g. during the second and third shifts) due to the availability of intelligent machines and system control software,
- *Production Flexibility*: Number of all part types that can be produced without adding major capital equipment.

The concept of flexible manufacturing systems was introduced in response to the need for mass customization and for greater sensitivity to changes in products, production technology, and markets. FMSs anticipate these variations through built-in flexibility a priori; hence they are more robust but have high initial capital investment cost. Flexible manufacturing systems were developed to address mid-volume, mid-variety production needs, by taking advantage of the similarities between parts in design and/or manufacture in order to achieve economy of scope. In this way, changes in work orders, production schedules, part-programs, and tooling for production of a family of parts can be addressed. In terms of design, FMSs possess an integral architecture (hardware/software), where the boundaries between the components and their functionalities are often difficult to identify and they are tightly linked together. Furthermore, it has fixed hardware and fixed, but programmable, software. This type of architecture does not allow changes to be made on the system structure. Therefore, FMSs have limited capabilities in terms of upgrading, add-ons, customization.

The need for an increased responsiveness of manufacturing systems directed the research efforts towards the concept of reconfigurability, that can be defined as the ability to repeatedly change and rearrange the components or a system in a cost-effective way.

Capability of reconfiguration will be the essential requirement for manufacturing systems to respond to unpredictable turbulence in environments. A manufacturing system must be able to dynamically change its configurations (for this reason the term “reconfiguration” is employed), in terms of its own structure as well as functional principles.

In this way, a dynamic reconfigurable manufacturing system (RMS) is realised. In literature, many definitions of RMS can be found. Koren (Koren, 1999), describes an RMS as a system designed form the beginning for rapid changes in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements. Liles and Huff (Liles, 1990) defined an RMS as a system capable of tailoring its own configuration to meet the production demands dynamically placed on it.

Therefore, there is no doubt that the RMS concept has been proposed to meet the changes and uncertainties of manufacturing environment, and this objective would be achieved by reconfiguring hardware and/or software resources. System reconfigurability can be classified in terms of the levels where the reconfigurable actions are taken. Reconfigurability at lower levels is mainly achieved by changing hardware resources, and reconfigurability at the higher levels is mainly achieved by changing software resources and/or by choosing alternatives methods or organization structures by flexible people. However, they usually work together so that system reconfigurability can be maximized cost-effectively, as shown in Fig. 2.4.

	Fixed Hardware	Reconfigurable Hardware
No software	Manual machines Dedicated lines	Convertible lines
Fixed software	FMS	Modular Machines
Reconfigurable software	Modular Open-Architecture Controller	Reconfigurable Machines and Controllers RMS

Fig. 2.4. Key hardware and software features of RMS.

On the basis of this argumentation, El Maraghy (El Maraghy, 2006) extended Koren’s definition stating that “a RMS has an ability to reconfigure hardware and control resources at all of the functional and organizational levels, in order to quickly adjust production capacity and functionality in response to sudden changes in market or in regulatory requirements”.

According to that definition, it is possible to understand why, in Fig. 2.2, Reconfigurable Manufacturing Systems are located in the middle between Dedicated systems and Flexible Manufacturing Systems, and the arrows indicate the capability of RMSs to adapt themselves in order to achieve various capacity and functionality objectives. This is certainly the key feature of RMS that, unlike DMSs and FMSs, takes advantage of capacity and functionality features that are not fixed (Mehrabi et al., 2000).

By summarizing, some considerations can be made on the characteristics of both FMSs and RMSs. While FMSs are built with all the flexibility, functionality, and capacity available, even, as in some cases, with those that may not be needed at installation time, RMSs are designed for a potential rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family. An FMS is a system whose machines are able to perform operations on a random sequence of parts of different types with little or no time or other expenditure for changeover, by using processing stations and material handling systems that are entirely under computer control (CNC). On the other hand, RMSs will enable the rapid changing of system components and the rapid addition of application-specific software modules, therefore they do it run the risk of becoming obsolete. They will be open-ended, so that it can be continuously improved by integrating new technology, and rapidly reconfigured. This means that flexibility can be achieved not only in producing a variety of parts, but also in changing the system itself, by using basic process modules hardware and software that will be rearranged quickly and reliably. In summary, it is possible to say that RMS is a manufacturing system with customized flexibility and FMS is a manufacturing system with general flexibility (Hu, 2005).

FMSs general flexibility is provided by the use of equipment with built-in high functionality, RMSs customized flexibility is provided by scalability and reconfiguration as needed, when needed, (Mehrabi et al., 2000). Flexibility is then a key factor also in reconfigurable manufacturing systems. In this sense, many authors notice that there are common grounds in philosophy between the FMS and RMS paradigms and support the idea that they represent a continuum, so that they predict that “the future Reconfigurable Manufacturing Systems will be more Flexible” (Stecke, 2005).

2.4 MANUFACTURING SYSTEMS FUTURE CHALLENGES

The concept of reconfiguration is certainly the fundamental target for modern manufacturing systems. The RMS paradigm has encouraged valuable research studies into areas of great interest for manufacturing systems reconfiguration feasibility, such as process and production planning, modular interfaces, and so on.

A number of technologies are available today to achieve physical and logical reconfiguration within manufacturing systems, but the implementation of RMSs still requires additional development in specific key technologies. Many open questions remain and several challenges represent attractive areas of research (Youssef et al., 2006a; Youssef et al., 2006b).

Among these challenges, the followings can be listed (ElMaraghy, 2006):

- measures for changeability, flexibility, adaptability, responsiveness, reconfigurability and their relationships,
- hardware and software enabling technologies,
- reconfigurable logical support systems, such as logistics, production planning and control, process planning, tooling, and fixtures,
- balance of hard and soft capacity and functionality scalability options,
- design of machines, systems, and controls oriented towards flexibility, reconfiguration and integration with current systems and software,
- models to determine the levels of flexibility and reconfigurability required for different applications,
- appropriate capacity scalability (both expansion and reduction) policies,
- lifecycle economic justification models for these paradigms,
- appropriate frequency of change or reconfiguration,
- rules for reconfiguration and changeability,

- smooth and optimal systems transition and changeover,
- changeability and reconfiguration dependent quality factors, including human-related issues,
- complexity measurement, reduction, and management techniques,
- the use of group technology to benefit from commonality and standardization of parts, operation sequences, product structure, platforms, engineering, and purchasing,
- “total productivity” measure, which considers all elements and all trade-offs.

New technologies are needed to address system design issues, software/hardware architectures, control requirements, and machine/tool design aspects.

At the system level, the different configurations to be used for producing a part family have to be accurately designed, thus design methodologies have to be developed and evaluation criteria should be defined.

The software and hardware should be based on "open architectures" so that additions and modifications are possible. Hardware and software should also be modular so that updating and adjustment are easier and less costly, as only a small part of the software/hardware is updated/modified. Practices like the "plug-and-play" component-based could be applied in such cases. Most of the control systems that exist today have fixed structure and are only partially programmable, thus inappropriate for RMSs.

Machine tools, robots, assembly stations and all hardware needed should be optimised for several configurations and uses, and therefore also made reconfigurable.

Moreover, RMSs should face a number of challenges to become widely accepted by the manufacturing industry. The major requirements for the introduction of RMSs are related to product variability, responsiveness, non-obsolescence, reliability and cost-effectiveness. In order to meet all these requisites, efforts are currently spent to further introduce the role of information technology in modern manufacturing systems. Following this direction, application of information technology in various stages of product design, production scheduling and process planning, machines control and processes monitoring (both on and off line), automation, quality control and networking and communication, and are now under deep study and are going through a rapid development.

In particular, the main area of research is the development and implementation of integrated tools for manufacturing engineering taking into account the reconfigurability of systems, towards the realization of one of the most important technologies of the future: the Digital Factory.

The concept is based on the employment of information technology and methodologies for distributed data management, tools for process engineering, tools for presentation and graphic visualization, participative, collaborative and networked engineering, interfaces to the reality.

This approach would allow to achieve the shortening of development time and cost as well as the integration of knowledge coming from different manufacturing processes and departments, and decentralized manufacturing of the increasing variety of parts and products in numerous production sites, and, finally, the focusing of manufacturing organizations on their core competences, working efficiently with other companies and suppliers, on the basis of effective IT-based cooperative engineering.

CHAPTER 3

DIGITAL FACTORY

3.1 INTRODUCTION

Manufacturing industry is going through a rapid transformation, determined by several factors including market globalization, that comes along with a strongly increased mobility of goods, people and capital, market saturation as well as rapid advances made in process technology. This trends contributes to magnify the effects of socio-economic events and market requirements in industry, and to increase competitiveness among players.

As these conditions characterise current manufacturing industry, the following requirements can be identified (Maropoulos, 2003):

- Highly agile and innovative corporations that can seize and exploit market opportunities, worldwide.
- Effective management of corporate revenue streams across major technology development phases.
- Development of dynamic supply networks and flexible manufacturing capabilities within the extended enterprise, based product's life cycle management.

The factory as a multifunctional and complex system has to be managed in view of the fulfilment of customer orders and economic objectives. More and more factories have to be seen as nodes within production networks. Their reliability, productivity and flexibility are influencing the manufacturing quality and costs and thus the overall efficiency of these networks (Westkaemper, 2007).

As discussed in the previous chapter, the changing manufacturing environment characterized by aggressive competition on a global scale and rapid changes in process technology requires manufacturing systems that are easily upgradable and into which new technologies and new functions can be readily integrated. These conditions require a responsive new manufacturing approach, such as the RMS paradigm, that enables:

- the launch of new product models to be undertaken very quickly, and rapid adjustment of the manufacturing system capacity to market demands;
- rapid integration of new functions and process technologies into existing systems;
- easy adaptation to variable quantities of products.

The manufacturing systems conceived according to this new approach must be rapidly designed, able to convert quickly to the production of new models, to adjust capacity and functionality, and to integrate technology in order to produce an increased variety of products in unpredictable quantities.

In order to stand competition in this global market, under the pressure of external and internal influencing factors, companies should take into account new technologies and innovations for future demands and development of the factory structures. The time-to-market of products as well as production facilities must be decreased (Westkaemper, 2007). For that reason, the development of methods for rapid product and process realization is currently one of the major elements of competitiveness for the manufacturing industry.

3.2 THE ROLE OF PLANNING IN NEW MANUFACTURING PARADIGMS

Maintaining facilities to meet the challenges of changing markets has become crucial to the company's success and a lot costly. Some main aspects lead to the demand for permanent improvement and adaptation of manufacturing systems and the factory structures. Changing order situations and the high dynamics of the capacity load require more technical flexibility including the permanent optimisation of the layout and structure of manufacturing systems. The shorter life time of products increases the frequency and volume of planning processes. As envisaged in the RMS paradigm, modern factories must be flexible enough to provide for multiple product series, and periodically a significant design change may require a complete reconfiguration, or the construction of an entirely new facility. It is interesting to notice that today's short product lifecycle results in a manufacturing systems life time much longer than the life time of products. The usual life time of a manufacturing system is higher than 10 years, while the life time of products is much shorter and is likely to become even shorter. Consequently, the layout and technical functionality of manufacturing systems have to be changed frequently and quickly in view of product requirements, economic objectives and the state-of-the-art of technologies.

As already discussed in the previous chapter, the structural flexibility of manufacturing facilities has been enormously improved during the last years, enabling companies to adapt their technical manufacturing structure with smaller investments and within a much shorter period of time, according to the RMS vision (Koren et al., 1999). The adaptation of the technical production structure, that is the set-up of the manufacturing system on different levels, will take place more often with a shorter planning horizon, thus becoming comparable to the known Kaizen, continuous process improvement (Westkaemper, 2007; Gregor et al., 2009). New structures and plant reconfigurations are now a liability, rather than an asset, and technical investments in manufacturing systems are "long-life products", which have to support companies strategies.

Factory planning is a multi-scale process, both in terms of time and data, since it has to cover a full time scale from the establishment to a long future perspective, and it should integrate knowledge coming from different manufacturing processes. The continuous improvement process on the manufacturing system level should be based on the planned production programme, constantly monitoring the real system structure and continuously developing and evaluating adaptation possibilities. The current production capacity and layout have to be changed and optimised according to the needs of the up to date production programme, which includes current customers requirements and suppliers capabilities. To implement this new paradigm of a continuous planning process, it is necessary to reduce the planning time (Westkaemper et al., 2001). As a result, manufacturing engineers are seeking to shorten every phase of production planning, including planning related to facilities. Because each variable offers considerable potential for savings, it is essential to access and analyze all the relevant data to better understand where costs could be reduced. An optimised planning process can reduce product lifecycle costs in the early stages of product development, and should be focused on the integration of manufacturing operations and factory planning oriented towards the medium-term objectives (Gregor et al., 2009).

Nowadays, the development of a production facility is carried out through team-work in well-defined phases. Any change, even the smallest one, brings risk of success. A systematic approach can reduce development time and costs and make the development process reliable (Worn). Innovative paradigms aiming at supporting the research and innovation in manufacturing engineering have been promoted: factory as a product, factory life cycle, factory data management and innovative platforms for design ad continuously optimization of factories, equipment and manufacturing processes. The continuous improvement and optimisation can be realised by means of new methods and new computerised systems for factory planning, as the tools of future manufacturing engineering and management are today digital and distributed (Westkaemper et al., 2001). According to the world leaders in technology development, the digital technologies will be the main driver of productivity and competitiveness improvement in 21 Century (Sacco et al., 2009). Digital tools allow the continuous planning of changes in factories (Westkaemper et al., 2001): besides the improvement of time and cost issues, their employment has a largely positive influence on the quality of the planning process for continuous improvement (Bracht et al., 2005).

The objective of the new Digital Factory concept is derived from this simple fact: the quality and fastness of changes can be supported by 3D digital models of production systems and a systematic and multi-scale data base. The objective is to secure products and processes during an early phase of development and also to accompany the evolution of products and production with the use of digital models.

According to this new concept, production data management systems and simulation technologies are jointly used for optimizing manufacturing before starting the production and supporting the ramp-up phases. Digital factory implementation would allow for, first, the shortening of planning time and cost, through the use of standard libraries, data integration and automation, second, the improvement of planning results quality, through systematic digital testing, third, the integration of knowledge coming from different manufacturing processes and departments, through integrated workflows, the ability to test alternatives and the visualisation of planning results (Chryssolouris et al. 2009; Haller et al., 2005)

The new concept of Digital Factory has been identified as a key research area for the implementation of the so-called “factory of the future” (Chryssolouris et al., 2009).

3.3 DIGITAL FACTORY CONCEPT

The Digital Factory can be defined as a “comprehensive network of digital models, methods, and tools, including modelling, simulation and 3D/Virtual Reality visualization, integrated by a continuous data management”(Chryssolouris et al., 2009). The aim of this set of software tools and methodologies is to comprehensively design, model, simulate, evaluate and optimize products, processes and systems before a new factory is built or any modification is actually carried out on an existing system, in order to improve quality and reduce time of planning processes (Bracht et al., 2005; Kühn, 2006; Chryssolouris et al., 2009). One of the main advantages of the Digital Factory is that all the aspects of a factory can be developed and improved until the physical manufacturing of a product meets the quality, time and cost requirements (Park et al., 2009). The Digital Factory provides solutions to design, evaluate, monitor and control an entire manufacturing system based on 3D CAD, simulation, database and computer networks. The Digital Factory paradigm can be employed in manufacturing engineering to verify and optimize many decisions, plans and operations, such as product design, equipment, process planning, factory layout design, production and material flow analysis or even OLP (Off-Line Programming) of various equipments. This is consistent with the vision of the factory planning process as a multi-scale process (in view of time and data) discussed in the previous paragraph: the Digital Factory has been on occasion defined as a "systematically and multi-scaling data base" (Westkaemper, 2007). Instead of consisting of individual planning activities, the Digital Factory approach focuses on a networked, computer-aided planning which includes all the actors involved in the planning process (Petzelt et al., 2010). Thus, the vision of the Digital Factory concept is based on the integration of methods and tools available on different levels to plan and test the product and the related production process from the early design phase to the operative control of the factory.

In detail, the digital factory integrates the following processes:

– Product development, test and optimisation.
– Production process development and optimisation.
– Plant design and improvement.
– Operative production planning and control.

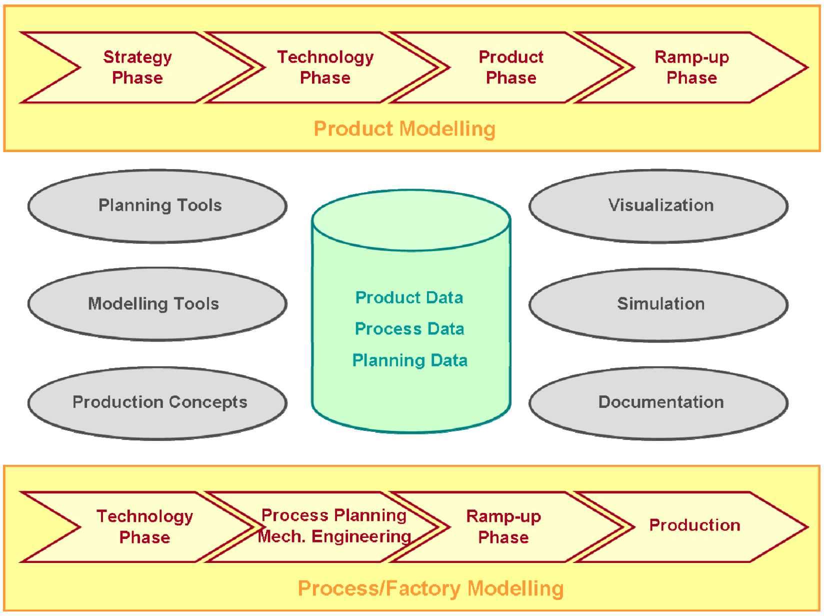

Fig. 3.1. The Digital Factory concept.

Data can be exchanged between systems, thus creating a cross-linkage of the necessary models and tools, considering static characteristics and systems dynamics (Wenzel). Hence, the envisaged interdisciplinary cooperation among various experts is possible all the way from the product design to the inspection of the new or modified factory. This approach takes part of a Product Lifecycle Management (PLM) approach that aims at sharing information relative to a product in each phase of its lifecycle (Cheutet et al., 2010). Data and models integration has been a core research activity to support the implementation of the Digital Factory approach. The introduction of consistent data structures for improving the integration of design and planning activities and consequently supporting a continuous data exchange has been investigated in literature (Pakkala et al., 2006). Some activities have focused on the definition of semantic correlations between the distributed models as well as the associated databases and the introduction of appropriate modelling conventions (Cheutet et al., 2010; Pakkala et al., 2006). On top of these developments, a number of methodologies for computer-supported co-operative development engineering, within a digital factory framework, have been published. Some researchers further suggested software architectures for relationship management (Chryssolouris et al., 2008). Distributed and hierarchic models reflect systemically a manufacturing system from process planning, layout planning, logistics planning, control planning to the dynamic evaluation of production systems. Based on the actual data and models, the planned products and production processes can be improved by use of modelling and simulation tools until the processes are fully developed and extensively tested for their use in the real factory (Westkaemper, 2007).

By summarising, a few main characteristics of the Digital Factory can be identified:

- Digitalisation. It is performed through the conversion of the real factory into a Digital Factory in order to realise simulation and/or virtual reality.
- Design and optimization based on simulation. Simulation and optimization tools can be employed together in order to carry out and optimize planning projects.
- Distributed and hierarchic integration. The complex factory planning can be decomposed into many hierarchies such as factory, workshops, production lines, cells and equipments which are harmonized and dynamic linked one to the other. By simulating each hierarchy, some aspects of manufacturing system can be optimized and validated including planning design, system capability, production line balance, planning process etc.

In this way, several objectives can be achieved through the employment of the Digital Factory approach (Westkaemper, 2007):

- Re-organization and/or optimization of a production line through simulation of the production cycle.
- Design based on a virtual prototype instead of a physical one, with consequent less time and money consumption. Reduction of production times and material waste based on permanent changes performed only virtually on digital mock-ups of new products.
- Evaluation of new machine and equipments, design and feasibility studies of material handling systems through simulation of their activities
- Training of workers, through recent technologies as the augmented reality, that allows to learn directly by using machines instead of reading manuals or instructions. Improved workers efficiency and safety through training and learning on virtual production lines and equipments or even training in emergency situation.
- Co-design of a product or production line, by means of a virtual network where different actors can collaborate and work together in a same environment. Collaboration among people working on the same project in different places but at the same time can be carried out.
- A common database permits to take care of every changes and keep trace of the past versions of the same product. The knowledge repository will be a common place where people can find any kind of stored material (designs or documents) in different versions.

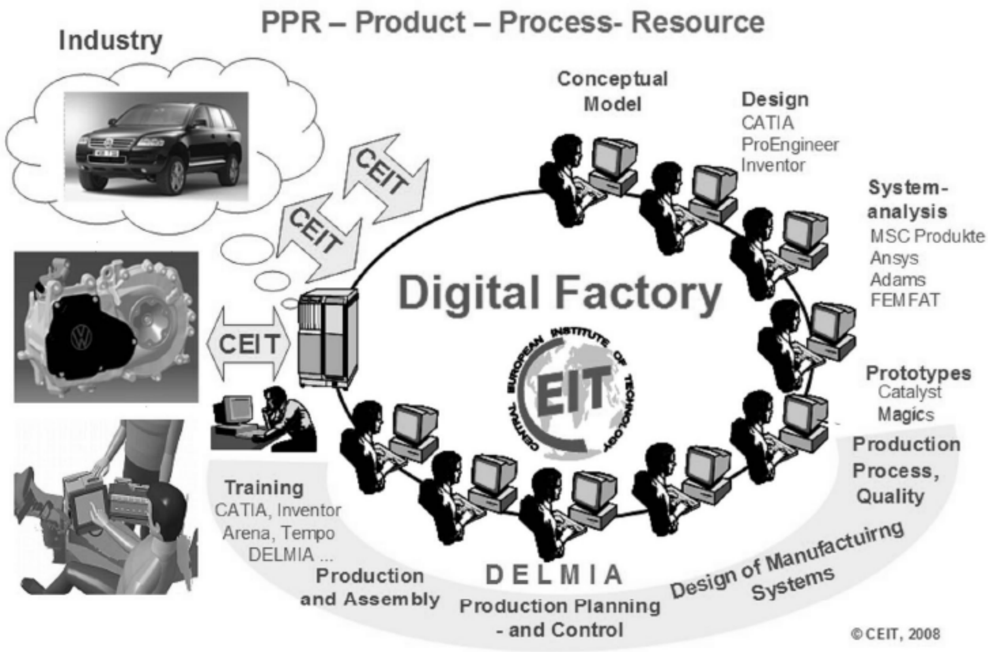

Fig. 3.2. Digital Factory concept (Gregor et al., 2005).

Digital factory links product development, production planning and facility planning (Wöhlke et al., 2005). Fig. 3.2 is one of the representations of the Digital Factory concept, integrating databases for product, process and factory modelling and advanced visualisation, simulation and documentation.

Digital Factory implementation results directly in organisational, technical and economic targets improvement, such as (Gregor et al., 2005):

- Improvement of profitability. Manufacturing costs can be reduced by optimisation of production equipment allocation, reduction in required area, better utilization of existing resources, reduction or full elimination of prototypes. Area savings by layout optimisation about 25%, cost savings by better utilisation of resources about 30%, cost savings by material flows optimisation about 35%, reduction in number of machines, tools, workplaces about 40%, have been noticed;
- Improvement of planning quality by standardisation of planning processes. The statistics show that product design and production planning influence about 80 % of production costs;
- Shorter product launch time. Thanks to this, payback period by investment in Digital Factory is very short. It is a consequence of the shortened product development, the reduction or full elimination of prototypes, machines and equipment off line programming saving time resources, etc. The Digital Factory enables product launching time reduction up to 25 - 50%;
- Improved product quality and reduction of risk for the introduction of a new product;
- Early validation of manufacturing processes. It is realised through various simulation tools;
- Transparent communication, through the employment of networks and common databases;
- Enhanced product knowledge dissemination through competent knowledge management;

– Reduction in errors. Digital Factory enables to test and reveal all possible production problems and shortages before start of production through validation of designed production concept, bottlenecks and collisions analysis;
– Increase in flexibility. It is due to faster production ramp-up and off-line validation of system changes;

Digital Factory is particularly suitable as a support for manufacturing of high sophisticated products, their planning, simulation and optimisation. Currently, the major application areas are automotive industry, aerospace and shipbuilding industries as well as electronics and consumer goods industries. The sector where the Digital Factory approach has been implemented for the first time is almost certainly the automotive industry, where excellent improvements were realised with regard to the following objectives:

– Planning of construction and operation of new plant for new car development
– Evaluation of design data at early design stage
– Evaluation of new machine and equipments, especially interference checks among jigs, fixture, products, facilities and robots
– Evaluation of new processes for new car production

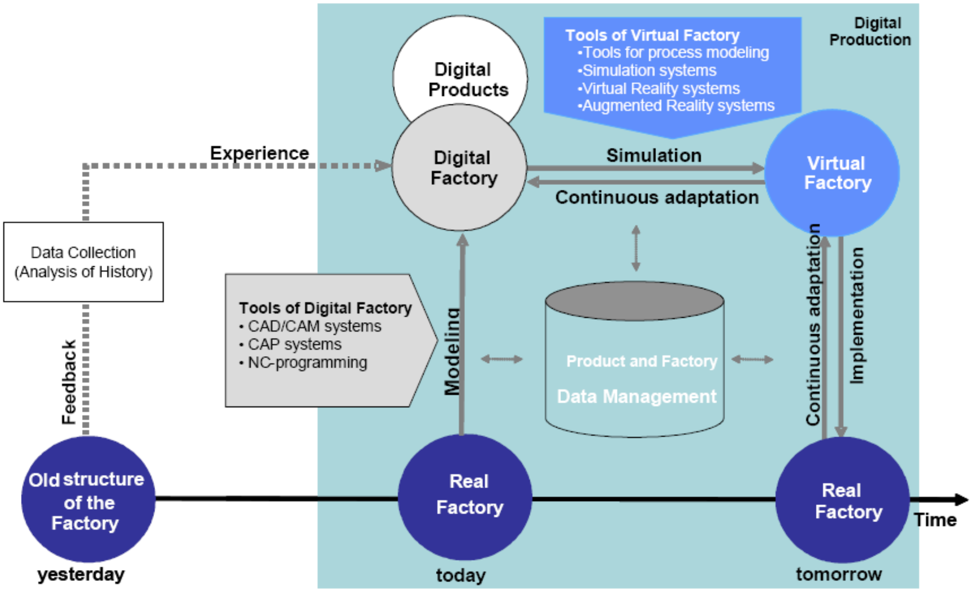

Fig. 3.3. Factory planning phases (Westkaemper, 2007).

3.4 DIGITAL FACTORY TECHNOLOGY

Within the Digital Factory approach, in order to achieve the objectives illustrated in the previous paragraph, new and innovative methods, technologies and tools have to be employed (Westkämper et al., 2002; Sacco et al., 2009). Digital Factory combines conventional manufacturing technology with digital methods (Chenhui et al., 2006). Its support technology includes several ICT (Information and Communication Technology) tools. Over the past few decades, the extensive use of ICT in manufacturing has allowed these technologies to reach the stage of maturity. The benefits of the new tools have been thoroughly examined and their efficiency in many applications has been demonstrated. Their application ranges from simple machining applications to manufacturing planning and control support. An example of the introduction of ICT, in the manufacturing world, is the concept of computer-integrated manufacturing (CIM). This concept was introduced in the late 1980s, favouring the enhancement of performance, efficiency, operational flexibility, product quality, responsive behaviour to market differentiations and time to market. However, the full strategic advantage of information technologies was poorly understood at that time and could not be exploited to its full extent. Then, inventory control and material requirements planning (MRP) systems were introduced in the 1960s and 1970s respectively. Such systems were further enhanced with the integration of tools capable of providing capacity and sales planning functionalities together with scheduling capabilities and forecasting tools. The result was the introduction of the closed-loop MRP. Nevertheless, the advances in microprocessor technology, the advent of the internet era, the standardization of software interfaces, the wide acceptance of formal techniques for software design and development, and the maturity of certain software products (relational database management systems and computer-aided design (CAD) systems, for instance) paved the way for facilitating the integration among diverse software applications. The evolution of information systems over the last decade has played a crucial role in the adoption of new information technologies in the environment of manufacturing systems. The following technologies have become crucial in manufacturing engineering:

2.1 Computer-aided technologies

CAD is considered among the technologies that have boosted productivity, allowing faster time to market for the product and dramatically reducing the time required for product development. The basis of the virtual engineering process is the digital mock-up, that encloses a realistic model of a product/facility and all functionality needed during the product/facility life-time. The system for the design of shop floor 3D layouts and generation of 3D models of production halls is missing in current Digital Factory solutions. It is possible to create the 3D model of production halls directly in CAD systems for new layouts or by new production systems designs, or Reverse Engineering technologies and 3D laser scanners can be employed to create 3D models of already existing production halls.

2.2 Manufacturing control

Integration of control systems with CAD and CAM and scheduling systems as well as real-time control, based on the distributed networking between sensors and control devices currently constitute key technologies under study.

2.3 Simulation

Computer simulation has become one of the most widely used techniques in manufacturing systems design, enabling decision makers and engineers to investigate the complexity of their systems and the way that changes in the system’s configuration or in the operational policies may affect the performance of the system or organization. Material flow simulation enables to optimise the movement of material, to reduce inventories and to support value added activities in internal logistics chain. The subsystems for effective ergonomics analysis utilise international standards as The National Institute for Occupational Safety and Health (NIOSH), Rapid Upper Limb Assessment (RULA), etc., which enable right planning and verification of man-machine interactions on the single workplaces. The highest level of analysis is represented by a computer simulation of production and robotics systems, which enables optimisation of material, information, value and financial flows in the factory.

2.4 Enterprise resource planning and optimization

Enterprise resource planning (ERP) systems attempt to integrate all data and processes of an organization into a unified system. A typical ERP system will use multiple components of computer software and hardware to achieve the integration. A key ingredient of most ERP systems is the use of a unified database to store data for the various system modules.

As regards the Digital Factory in particular, it is implemented by the synthesis of technologies and systems from five main technical areas, the Digital Factory ‘cornerstones’, corresponding to the design of product, process, factory, technologies for ensuring the conformance of the digital with the real environment, and the design of the enterprise (Maropoulos, 2003).

The main technical cornerstones of the Digital Factory are the followings:

1. Distributed and collaborative design.
   Product design within a collaborative and distributed network is the first technical cornerstone of DET.
2. 4.2. Process modelling and process planning.
   Process modelling and process planning research has substantially enriched the interface with the design environment with feature-based and object-oriented methods for manufacturing and assembly, enhancing interoperability with product modelling.
3. Physical-to-digital environment integrators.
   The physical-to-digital environment integrators represent a wide range of technologies that can be used for the bi-directional transfer and communication of data, models, measurements as well as process status and expert feedback between the digital and the physical domains.
4. Enterprise integration technologies.
   This technical category includes methods for Product Data Management (PDM), together with technologies for real-time management, planning and scheduling of production such as production planning and control (PPC) and enterprise resource planning (ERP) systems as well as methods for the formation and management of supply networks.
5. Advanced factory equipment and layout design and modelling.
   Factory and equipment modelling and optimization technology have two main elements: 3D technology for production equipment modelling and representation and methods for factory modelling and optimization.

The rapid advances in 3D graphics modelling methods combined with the rapid development of fast computer processors have allowed the accurate modelling and visualization of complex production machines using detailed, 3D solid models, with associated kinematic and dynamic properties. These can be used for modelling and analysing the processes required for manufacturing of discrete parts modelled in the design phase, such as machining, casting and deformation processes. Specially defined computational models are used for analysing key interactions between the material being processed and the machine elements including chatter analysis for vibration prevention in machining, finite element analysis (FEA) models for stress calculation in dies during material deformation, and thermal models for the prevention of thermally induced deflections during welding.

In terms of assembly processes, kinematic and dynamic models are used to analyse robotic manipulation and assembly of parts together with DFM/DFA (Design For Manufacturability/Design For Assembly) systems that simplify design to improve deliverability.

In conclusion, the convergence of computational analysis, materials modelling and 3D manufacturing equipment modelling tools will enhance the theoretical understanding of processes as well as improve machine design and process control. Methods for factory design and optimization have traditionally focused on the design of cells for modular or cellular manufacture. The contribution of cluster analysis and operations research work for optimizing the factory elements and the flow of products has been very significant (Baker et al., 2000). Many clustering algorithms have been defined for the identification of similarities between processing requirements of parts and the subsequent creation of production cells. A recent effort relates to cell design and positioning within the factory, an activity that can be carried out without the requirement for the involvement of cluster analysis experts (Baker et al., 1997). These methods allowed the limited interlinking with discrete event simulation systems via the exchange of spreadsheet files that contained key routing and machine positioning and availability data. The advent of 3D equipment and factory modelling tools necessitates the development of a new generation of factory design and visualization tools that will combine the traditional optimization techniques with new methods for factory modelling based on the rapid re-engineering of physical resources, and the definition of re-configurable facilities that deliver the required business responsiveness.

Currently, different types of software are linked in PLM solutions, which control different parts of the manufacturing cycle. Computer Aided Design (CAD) systems define what will be produced. Manufacturing Process Management (MPM) defines how it is to be built. Enterprise Resources Planning (ERP) answers when and where it is built. Manufacturing Execution System (MES) provides shop floor control and simultaneously manufacturing feedback. These are based on a similar concept: the various software tools are mutually networked: the object is to ensure that all planning results are always completely up to-date and are available to the authorised users at all times. With these concepts and by using a large spectrum of simulation application/systems a virtual and scalable system constitutes the platform for high-end visualisation of the planning results and thus facilitates interdisciplinary communication among various experts despite differences in specialised terminology. Two advanced digital factory/manufacturing concepts are currently offered by Dassault Systemes and Tecnomatix: a few solutions from other companies are also available on the market.

3.5 Simulation Methods for the Digital Factory

The previous paragraph presented the role of digital technology tools in the implementation of the Digital factory concept. Simulation is a key factor for the success of this approach and can have several uses on the basis of the category of the simulation software tool employed. For example, modelling and simulation of a digital mock-up of a manufacturing system can be employed to analyse the system's production performance, through Discrete Event Simulation (DES), or can be adopted to analyse layout, ergonomics and robotics issues, through 3D motion simulation (Kuehn, 2006; Caggiano et al., 2010, Westkaemper, 2007).

As already discussed in the previous paragraphs, the Digital Factory involves all enterprise layers and all time horizons, from strategic planning to operational optimization. In this context, a structured representation of the Digital Factory on six levels of details, shown in Fig. 3.4, that can help identify the various simulation requirements has been proposed (Boime, 2005).

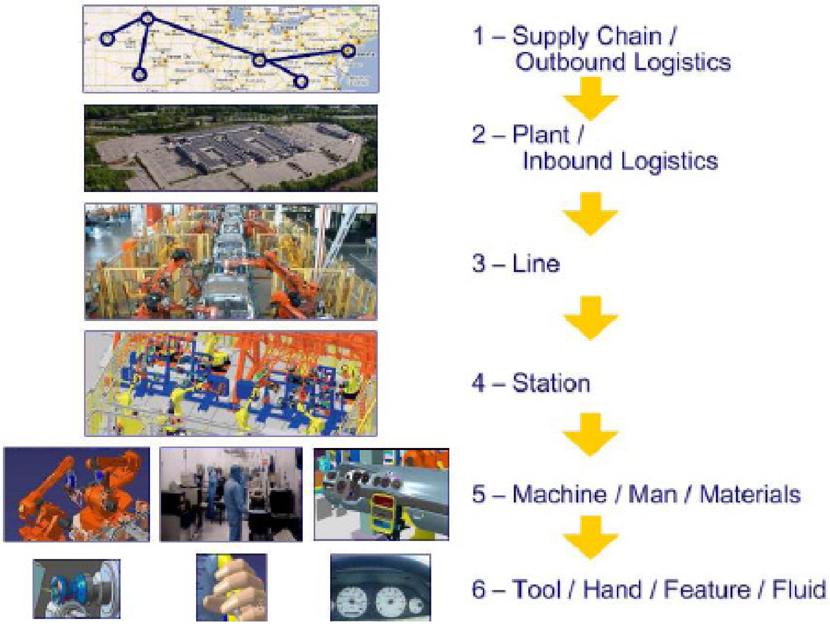

Fig. 3.4. Different Layers and Simulation Requirements in the Digital Factory (Boime, 2005).

These layers correspond to specific needs for design and simulation of manufacturing systems behaviour, and accordingly to specific actors of the production system development process, with their own tools and methodologies. For example, at level 1 or 2, the objective can be the analysis of the physical supply flows inside the extended enterprise. At level 3, the objective can be the validation of a physical layout inside the plant and a line rate. At level 5or 6, the objective can be the validation of the settings of a manufacturing program in the production environment (robots, CNC machining, etc.). For each layer, specific simulation tools corresponding to specific actors, with different geometric representations and different simulation structures can be identified (Cheutet et al., 2010). The Digital Factory approach requires data consistency among all these levels and subtasks.

Typical simulation applications in the Digital Factory are (Kuehn, 2006):

– Layout planning and simulation for layout validation and optimisation
– Static analysis and dynamic simulation of logistic and production flows
– Line balancing of assembly processes
– Simulation of complex material handling
– Robotics and complex motion
– Simulation of part manufacturing
– Simulation of human resources
– Ergonomic simulation
– Simulation of production logistics
– Simulation for control software testing
– Simulation for operative production control

Following, the main applications of simulation for the Digital Factory implementation are illustrated.

Factory Design and Layout

CAD tools for factory layout planning provide the possibility to sketch in a 3D environment as well as to employ predefined modules for creating detailed factory models. These layout tools allow to work with 3D objects that virtually represent the resources used in a factory, from floor and overhead conveyors, mezzanines and cranes to material handling containers and operators. Virtual reality models enable to move through factory mock-ups, walk through factories, inspect, and animate motion in a rendered 3D-factory model. This design and communication technology also provides design collaboration activities in order to view, measure, analyse, and inspect for clearance in a 3D-virtual factory model.

OPTIMIZING THE FACTORY FLOW

Simulation tools can be employed to represent material flow in specific scenarios and compare the results from alternative layouts and logics. Factory layouts can be analyzed by using part routing information, material storage requirements, material handling equipment specifications, and part packaging information. Material flow studies can be performed on alternative layout configurations and layout options can be compared in order to find the best layout and to improve production efficiency. With dedicated analysis tools, bottlenecks are detected easily and the layout can be redesigned.

PLANT, LINE AND PROCESS SIMULATION

Plant, line and process simulation can be performed by means of Discrete Event Simulation tools. These tools allow to analyse systems and processes in order to improve material flow, resource utilization and logistics for all levels of plant planning. This includes planning of global production facilities, through local plants, to specific lines.

Discrete event simulation technology allows to:

- Minimize the investment cost for production lines while meeting the required production demands.
- Detect and eliminate problems that otherwise would require cost- and time-consuming correction measures during production ramp-up.
- Improve the performance of existing production systems by implementing measures that have been verified in a simulation environment prior to implementation.

Simulation models enable to run experiments and what-if scenarios without acting directly on an existing production system. It allows to explore system characteristics and optimise the performance of the planned production and logistic systems before establishing the actual systems. Large benefits for the production planning process are achieved especially for production systems with complex system dynamics.

PART MANUFACTURING

Part manufacturing applications require to link the tasks of the manufacturing engineer, NC programmer, tool designer and tooling manager, while extending access to the shop floor. Similarly to robot programs, NC-programs can be created in the digital environment. The virtual work piece is defined by the product model. Given a model of the raw material, an NC-program can be created in the virtual reality. The 3D-simulation of NC paths enables to detect collisions, analyze material removal and reduce cycle times. After testing and optimizing with regard to cycle times, the NC-program is transferred into the real NC machine. Further detailed process information can be delivered to the shop floor, and NC tool paths can be created taking into account cycle times for each set of features and operations.

SIMULATION OF ROBOTIC WORKCELLS

Digital manufacturing and simulation of robotic workcells focus on the design, simulation, optimisation, analysis and even offline programming of robotic workcells and automated manufacturing processes. This requires a concurrent engineering platform to model the mock-ups of manufacturing cells on 3D graphics to optimise processes and calculate cycle times. Robots and mechanisms including 3D path definition are required to perform accessibility checks, collision detection and optimisation of cycle time.

Typical applications are:

– Workcell layout design and modelling from 3D CAD data.
– Robots, machines, tools and equipment libraries.
– Modelling of complex kinematics of robots and other mechanisms.
– Robot calibration to improve accuracy.
– Automatic path planning.
– Collision detection.
– Sequencing of operations (SOP).
– Offline programming (OLP).

Models have to implement the physical and control characteristics of robots and other automated devices. Robot offline programming requires accurate simulation of robot motion sequences in order to download machine programs to the real controller on the shop floor. Controller specific information, including motion and process attributes, has to be added to the generated robot paths. Fig. 3.5 shows an example of robotic workcell simulation for the synchronization of activities among multiple robotic resources.

Fig. 3.5. Simulation of a Robotic workcell.

REALISTIC ROBOT SIMULATION (RRS)

In order to improve modelling, simulation and offline programming of robot applications regarding the dynamic and absolute position accuracy a virtual Robot Controller (VRC) interface has been introduced. This interface enables to integrate the original software of controllers for industrial robots almost completely into simulation systems in a standard manner. A typical application in the robotic field addresses the entire spot-welding design and programming process. Designing a spot-welding cell layout by directly accessing CAD models, optimizing robot placement and path and selecting the best welding gun are required features. Critical factors such as spatial constraints, geometric limitations and welding cycle times have to be taken into account. The main features in this kind of application are gun search, automatic robot placement, path cycle-time optimizers, and weld point management tools. These enable to create virtual cells, simulations, and programs that accurately reflect the physical cell and robot behaviour. Finally, robot programs and the sequence of operations can be generated and verified for the application, and the PLC programs can be created automatically.

MODEL BASED PLC OFFLINE PROGRAMMING

The PLC program generation can be part of a 3D-integrated virtual environment which allows to work in parallel and share information from both the mechanical design and the control departments. This enables the automatic generation of PLC programs directly from the virtual manufacturing model, and allows for extensive virtual tests prior to building the equipment on the shop floor. Benefits include:

- Visualize and optimise functionality and behaviour early in the production engineering phase.
- Increase the speed, consistency and reliability of design processes.
- Prove the feasibility of the control logic.
- Correct logical errors well before ramp-up.
- Cut time and cost by creating shop-floor documentation off line.
- Evaluate PLC program changes on a virtual model instead of taking risks on real equipment.

The integration of model based automatic offline programming including simulation and verification by use of a virtual manufacturing model and applying real automation data can optimise the engineering process and help to significantly cut ramp-up times (Schloegl, 2006).

Human Resource Simulation

An accurate modelling, simulation and analysis of manual assembly designs, manual workplaces and human operations with detailed 3D virtual human models can reduce execution times and prevent work-related health problems.

Human resource simulation focuses on:

- Detailed design of manual operations.
- Checking the feasibility of tasks.
- Ergonomic analysis.
- Time analysis.
- Generating work instructions.

Human resource simulation improves workplace ergonomics, assembly cycle times, and communication of planning results, increases productivity of production facilities, generates a comprehensive documentation of human operations and promotes the reuse of best-practices. The evaluation and effective design of manual workplaces can help to raise the motivation of workers on the shop floor and therefore increase profitability.

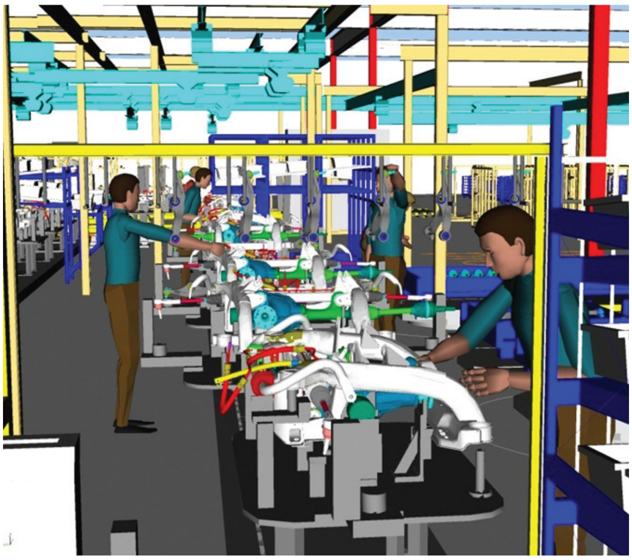

Fig. 3.6. Human Resource Simulation.

Dynamic Line Balancing

Line balancing and machining planning require to calculate operating cycle times and to generate for instance a corresponding NC tool path. Discrete event simulation models provide a dynamic perspective of the balanced production line. They allow to analyze throughput, work-inprocess, resource utilization and buffer sizes in order to improve the line balancing.

With the help of the illustrated tools, based on the analysis of simulation, manufacturing systems can be optimized and validated in terms of planning design, system capability, layout planning, production line balance, collision detection, planning process, etc.

The main benefits from the application of simulation tools can be summarised as (Fowler et al., 2004):

- Time compression – the potential to simulate years of real system operation in a much shorter time,
- Component integration – the ability to integrate complex system components to study their interactions,
- Risk avoidance – hypothetical or potentially dangerous systems can be studied without the financial or physical risks that may be involved in building and studying a real system,
- Physical scaling – the ability to study much larger or smaller versions of a system,
- Repeatability – the ability to study different systems in identical environments or the same system in different environments,
- Control – everything in a simulated environment can be precisely monitored and exactly controlled.

As illustrated, the Digital Factory involves the use of simulation along the entire process chain, from developing of new product, planning the associated production equipment and organizing mass production. Therefore, it involves more than the simple use of simulation tools. All activities in the plant – that means the whole workflow - have to be standardized (Arndt, 2006). The data outcome of every step of the workflow has to be specified and the data of the workflow, when a step is finished, should be stored into a global factory wide database.

Models created for one purpose can potentially be used to provide support for other tasks. This requires that the simulation models can be fed with historical data as well as with snapshot data. Furthermore, the models must be able to communicate with other business software. Furthermore, the expanded and continuously updated models provide a good tool to study the effect of for instance planned new product introduction in existing manufacturing systems (DeVin et al., 2004).

The integration at the base of the digital factory requires powerful interfaces and database systems for the joint use of actual data and modules between different complexity levels (vertical integration) and between the operational function areas (horizontal integration).

This aspect is really important, since the success of simulation depends on the quality and actuality of the available data. At any moment, simulation must have access to the up to date data of development and planning. The gap between the simulation models and the actual behaviour can be closed by connecting simulation systems with the control systems or data mining systems (Westkaemper, 2007). Fig. 3.7 represents the role of simulation in the vision of the digital factory, where all the tools and applications are connected to a central database.

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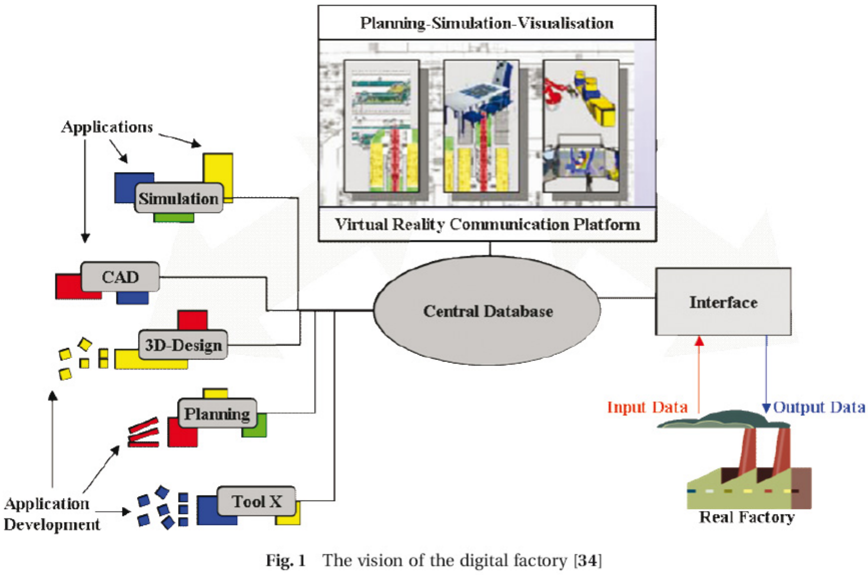


Fig. 3.7. Vision of the digital factory.

3.6 DIGITAL FACTORY FUTURE CHALLENGES

The implementation of the digital factory will result in huge savings in time and costs, but efforts are necessary for an effective implementation (Bracht et al., 2005).

In the current developmental status of the digital factory, many issues still require deep investigation (Haller et al., 2005):

– Concerning software and methods, issues such as integrating planning and layout data, exchanging data among different simulation tools, integrating and managing large amounts of data, improving software performance and extending the existing software planning functions and planning methods are dominant.
– As regards processes, attention will be concentrated towards complexity management. Roles, responsibilities, information flows and schedules need to be defined more precisely, and also described more clearly and simply.
– Organisational changes need to be extended. For example, as well as design engineers and planners, production staff (supervisors and operators) will increasingly take part in digital process. In addition, organisational models allowing greater integration of suppliers into digital production planning need to be developed and implemented.
– With regard to changing the behaviour and attitude of staff to the Digital Factory, the goal is to increase motivation through participation, which means that all staff concerned must now be included in training programmes and courses.

In (Bracht et al., 2005), four major problem fields resulting from the implementation of the digital factory have been identified, as shown in Fig. 2.

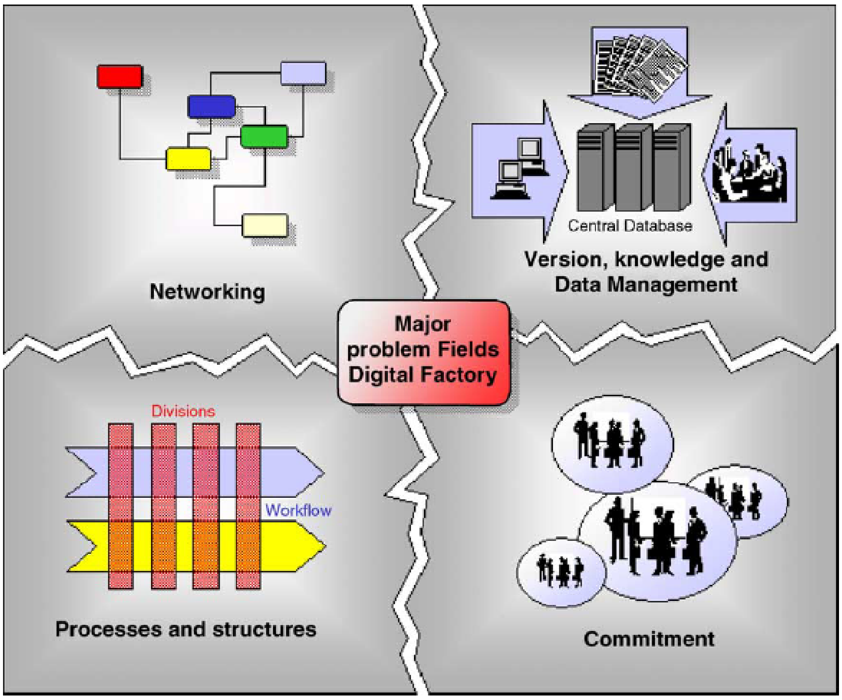


Fig. 2. Problem fields associated with the digital factory.

Fig. 3.8. Problem fields in the Digital Factory implementation (Bracht et al., 2005).

The realisation of the digital factory concept needs various software components such as design and planning software or simulation tools. All these have to function closely together. A single software system cannot cover the complete range of required functionalities: this can be achieved with the use of specialised software systems and their integration.

The fundamental requirement of comprehensive networking among all software tools involved in the production processes and in factory operation is difficult to achieve because of their predominantly proprietary design. Native formats give rise to a large number of interfaces, so that cooperation among the various tools results hard or even impossible. The effort for the conversion of the required data is still huge at present.

As regards data management, frequent data back-ups cause a large number of data-record versions to be stored during a project, in order to ensure the continued availability of the data in the event that they are needed again. Furthermore, identical data are often stored redundantly on various servers and systems.

A further challenge results from the necessity of managing and securing a company's specific knowhow in a manner appropriate for preventing loss. Workflows and experience must be recorded in such a way that they are available and useful to all employees.

Obsolete data-record versions and insufficient information flows represent sources of error which should not be underestimated. Since development and planning process is characterized by a multiplicity of iteration loops, adaptations are absolutely necessary in all departments of the company and in all phases of project execution. Particularly in the digital factory, special demands are imposed on the maintenance of data and the management of versions in this respect. It must be ensured that up-to-date, subject-specific, relevant data are continuously and immediately available to all those concerned, especially in the event of changes.

The large quantities of data and the equally large number of different data formats constitute one of the main challenges associated with the digital factory.

The first major challenge connected to data consistency inside the Digital Factory is related to the heterogeneity of tools and methods, in particular between the different simulations.

The Digital Factory implementation requires cost-effective and consistent data sharing between all the digital planning tools. Today there are no open, standardised, and universally accepted data sharing or intermediate formats capable of covering the whole chain (Daniels).

Future work will focus on open standard interfaces available for integration of various software tools into the digital factory system architecture. In recent research studies, different solutions have been envisaged. To enable re-use of the existing data, some proposed to put e.g. database tables into HTML (HyperText Markup Language) for viewing the product information on a browser. The problem is HTML basically just tells content how to display. Another solution is to digitize this information and maintain the relationships by use of XML (eXtensible Markup Language). It provides a highly defined way to automate the transfer of BOMs (Bill of Materials), assembly instructions, engineering definitions, manufacturing information, and so on, downstream. The use of XML is transparent to most designers. However, it can be helpful to understand how XML portrays CAD data in digital product pipelines. According to many authors, communication between systems is only possible if there is a shared understanding of the meaning of the exchanged data. Ontologies are an effective mean to acquire such a shared understanding. Automatic matching of ontologies involves the creation of mapping rules or alignments, i.e. finding sets of correspondences between the ontologies (Thomalla, 2010).

Other research studies propose the employment of Application Protocols, i.e. application-specific data models, for the standardized representation of planning data in a specific application context. The data model of an Application Protocol enables the software developer to implement standard software interfaces in planning tools. Thus, Application Protocols can contribute to increase the integration ability of software tools (Petzelt et al., 2010).

Finally, the importance of defining a common ontology for concepts to make the use of terms as consistent and harmonized as possible has been stated. Consistent use of terms is a key to make information from different sources easily integrated. Proposed approaches focus on knowledge management based on ontologies and existing information standards (Kjellberg et al., 2009).

The second challenge connected to data consistency inside the Digital Factory is related to the heterogeneity of models used for simulation (Cheutet et al., 2010). As illustrated, diverse simulation families are currently available and they employ different models containing various levels of information. Several research efforts are currently spent to simplify the work with Digital Factory models (Wenzel et al., 2005). Different approaches have been proposed. For example, (Wenzel et al., 2005) present an approach which introduces modelling conventions based on a common world view of its users by applying the metaphor of the Electronic Catalogue as well as a well-defined workflow. In (Lin et al., 2007), a general Manufacturing System Engineering (MSE) knowledge representation scheme, called an MSE ontology model, to facilitate communication and information exchange in inter-enterprise, multi-disciplinary engineering design teams has been developed and encoded in the standard semantic web language. (Cheutet et al., 2010) propose a framework defined by a set of multi-layered models of the product and production system, linked through their structural representations. The next step will be to define the different multi-layered models for the different simulation models that are used in the Digital Factory and to create links between all the structural layers.

Moreover, since models are developed by different persons with different responsibilities, like engineers or simulation experts, the single modelling processes in the Digital Factory result in individual and ambiguous models. The different requirements referring the model structure and behaviour have led to a situation in which, even for one and the same object of investigation, a great number of models from different points of view have been developed. On the way to the integration within the scope of the Digital Factory, starting from application, models have to be classified related to suitable criteria in order to identify similarities, differences, dependencies and overlapping (Wenzel et al., 2005).

Many research studies have been conducted and are still in progress in order to investigate the and develop new solutions for the described problems (Sacco et al., 2009).

The identified research priorities include the development of integrated tools for industrial engineering and adaptation of manufacturing, taking into account the configurability or partial autonomy of systems, the development of a standard data model of factories and the management of factory data, including open networks of engineering and real-time management of manufacturing data (Chryssolouris et al., 2009).

CHAPTER 4

DISCRETE EVENT SIMULATION OF MANUFACTURING SYSTEMS

4.1 INTRODUCTION

The fundamental role of simulation as a key technology for the Digital Factory concept implementation has been widely discussed in Chapter 3. Two main families of simulation tools for manufacturing systems analysis have been identified (Cheutet et al., 2010):

- Discrete Event Simulation (DES), consisting of elements that react to some events, that is employed for flow simulation, control simulation, virtual reality, etc.
- 3D simulation, sometimes defined "prescriptive", where actions are carried out at a defined given instant, and that is employed for layout analysis, offline programming of robots, ergonomics simulation, etc.

The aim of this chapter is to introduce the main features and applications of Discrete Event Simulation (DES), and illustrate how one of the most utilised DES software tool works.

Nowadays, DES is one of the most widely used methods to study, analyze, design and improve manufacturing systems, since it allows to evaluate the system's performance under different configurations of interest and over a long period of real time (Caputo et al., 2006). The general benefit of simulation in manufacturing is that it offers a system-wide view of the effect of any changes on a manufacturing system, whether it exists or not. It has become the pre-eminent method for analyzing the modern complex manufacturing systems, where purely analytic tools prove more and more difficult to use compared to the past. The high levels of automation and integration, and the complex interactions among systems elements make the manufacturing systems so complex that a comprehensive planning approach is needed to carry out the continuous improvement required by the industry. This improvement involves the enhancement of the manufacturing system sub-systems or components, as it is a collection of entities which all work together for the benefit of the whole. When a change is made in any of the components, it affects the other entities and the behaviour of the system as a whole. The components of a manufacturing system are represented by facilities, equipment, tooling, material handling systems, people, as well as production methods or procedures, i.e. a collection of physical elements and procedures working together to accomplish specific manufacturing tasks resulting in components or end products. Therefore, every enhancement of such a complex system should be designed following a systematic and comprehensive approach, with consequent difficulties and complexities concerning the analysis and evaluation of the system's performance (Chenhui et al., 2010).

Any new facility addition or rearrangements of available facilities (such as repositioning machines, changing daily part schedules or shift schedules, managing process cycle times, reassigning available operators, modifying the quantity of operators or machines, etc.) directly affect the balance of facilities utilization and production flows. Although the suggested changes in the system anticipate certain upgrades in the manufacturing cell performance, the system needs to be analyzed and consequences of the suggested changes should be verified in carefully before going ahead with investments. When the implementation of a new solution in the system needs the quick analysis and visual examination of changes before carrying out actual modifications in the system, simulation modelling becomes essential. It is a practical methodology for understanding the high-level dynamics of a complex manufacturing system, and in recent years, it has been significantly enhanced by increasingly powerful computational platform.

Discrete event simulation models are helpful to answer detailed questions about how a complex manufacturing system will perform (Fowler). DES allows the user to experiment with different “what if scenarios and to develop the most efficient work flow by exploring what could happen applying different alternatives (Old scenarios).

Discrete event simulation offers a powerful tool to easily modify a digital facility for different manufacturing scenarios, where the user can change several types of input parameters such as: repositioning machines, changing daily part schedules or shift schedules, managing process cycle times, reassigning available operators, modifying the quantity of operators or machines, and experimenting with material flow routing logic selection. This is very useful for productivity and cost analysis, bottlenecks identification and machine failure simulation, production plan verification, WIP (Work In Progress) analysis and JIT (Just In Time) scenarios. It is typically used to investigate manufacturing systems during their design and operational phases, and is also employed as an evaluating and modelling tool in scheduling. Moreover, DES can generate reports and detailed statistics describing the behaviour of the system under study. Analytical results can be displayed in customizable numerical tables, bar graphs, pie charts, histograms, and time series graphs. Data can be exported to an external analysis tool such as a spreadsheet or other charting package (e.g. Excel). Based on these reports, the physical layouts, equipment selection, operation procedure, production flow planning, resource availability and utilization, etc. can be effectively implemented.

4.2 APPLICATIONS OF DISCRETE EVENT SIMULATION

The application of Discrete Event Simulation is oriented towards a number of questions concerning manufacturing systems design or redesign for production improvement.

Typical applications of DES are the followings:

- An explorative study of an existent system to find possible improvements (the simulation model is used to rapidly make a number of changes to see if the system can be improved by, e.g. changing scheduling rules, operating rules, or the system itself).
- Study an existent system with some suggested changes and compare the results to see if the changes are profitable (the model is used to validate the proposed changes, not to find them).
- Design and validate a new system (the simulation is used in the design process to validate the performance or functioning of the system, and detect possible enhancements).

In particular, the following specific issues can be addressed through DES (Hosseinpour et al., 2009, Law et al., 1998):

The need for and the quantity of equipment and personnel
- Number and type of machines for a particular objective
- Number, type, and physical arrangement of transporters, conveyors, and other support equipment (e.g., pallets and fixtures)
- Location and size of inventory buffers
- Evaluation of a change in product volume or mix
- Evaluation of the effect of a new piece of equipment on an existing manufacturing system
- Evaluation of capital investments
- Labor-requirements planning

Performance evaluation
- Throughput analysis
- Time-in-system analysis
- Bottleneck analysis

Evaluation of operational procedures
- Production scheduling
- Inventory policies
- Control strategies [e.g., for an automated guided vehicle system (AGVS)]
- Reliability analysis (e.g., effect of preventive maintenance)
- Quality-control policies

Following are some of the performance measures commonly estimated by simulation:
- Throughput
- Time in system for parts
- Times parts spend in queues
- Queue sizes
- Timeliness of deliveries
- Utilization of equipment or personnel

DES offers the opportunity to increase the system's performance, identify its possible weaknesses, or the effects of different strategies (controls and policies), and to check economical potential and investments for a relatively small expenditure. Performing a simulation before the purchase or installation of any equipment can help to avoid costly errors, speed up commissioning and ensure the plant operates right from the first time.

Some of the objectives that can be achieved through DES are:
- Shorten new product introduction, time-to-market, and time-to-volume.
- Improve production layout and minimize investments.
- Ensure that machines and equipment are in the right place.
- Ensure that sufficient material handling equipment is available.
- Optimize buffer sizes.
- Ensure that product handling is kept to a minimum.

In the last decades of the past century the application of DES in Europe was pushed mainly by automotive industry. Nowadays, it is applied to a number of production systems, from the production of airplanes to that of cars or hair dryers, from the work in shipyards to the highly automated white body production and paint shops in automotive industry. Therefore, there are also many differences in the objectives and the requirements for simulation models.

4.3 DISCRETE EVENT SIMULATION SOFTWARE TOOL: DELMIA QUEST

Nowadays, several Discrete Event Simulation software tools are available. Some of them, such as ARENA, are 2D software tools more focused on numerical output (concerning reliability, productivity, efficiency, bottlenecks detection) than on the graphic representation of the plant, while others allow a 3D visualization (Caputo et al., 2006). Among these 3D software tools, the most commonly utilised are almost certainly DELMIA QUEST from Dassault Systèmes and Tecnomatix Plant Simulation from Siemens PLM Software.

In this research work, DELMIA QUEST (Queuing Event Simulation Tool) software tool has been employed to carry out Discrete Event Simulation activities on manufacturing systems.

DELMIA QUEST provides an object-based, discrete event simulation environment combined with powerful visualization and robust import/export capabilities, conceived to model and analyse complex systems. It can simulate the flow of material, or discrete event processes allowing users to visualize accurate 3D representations of the manufacturing process and its behaviour over time. It provides 3D geometrically and dimensionally correct models, which operate at user-defined speeds, including real time. It can be suitably employed for production flow and process modelling, analysis and simulation. A single environment is provided for both building and running the model, allowing instant visualization of any model change: thus lengthy edit/ compile/ run/ analyze cycles are eliminated.

Moreover, it allows to compare data from multiple runs, parameters, and share the analytical data with custom reports and data files. Simulation results can be presented with model animation, reports, charts, etc. Analytical results can be displayed in customizable numerical tables, bar graphs, pie charts, histograms, and time series graphs. Data can be exported to an external analysis tool such as a spreadsheet or other charting package (e.g. Excel).

Within the various scenarios, the user can modify several types of input parameters such as: repositioning machines, changing daily part schedules or shift schedules, managing process cycle times, reassigning available operators, modifying the quantity of operators or machines, and experimenting with material flow routing logic selection.

The software provides a wide range of logics and policies (e.g. routing logic, process logic, buffering policies, built-in push and pull production attributes etc.) as well as many options to model a complex production system. If any new/customized logic is required, it can be built/edited using Simulation Control Language (SCL) or Batch Control Language (BCL).

In the following paragraphs, the key features of QUEST will be introduced to provide an understanding of the structure of the software in different sections concerning user interface, modelling features, simulation run and simulation results reporting features.

4.3.1 USER INTERFACE FEATURES

The QUEST Graphical User Interface (GUI) for Windows platforms is a Windows-style interface, where five main areas can be identified as shown in Fig. 4.1.

Models are shown in the middle part of the screen. The menus at the top of the screen connect to the broad areas of functionality in QUEST. The pages on the right of the screen, showing the action buttons that provide specific functions, are displayed according to the selected menu item. Finally, the world controls give the opportunity to manipulate and move around the world (Model, CAD or Draw) that the user currently working with.

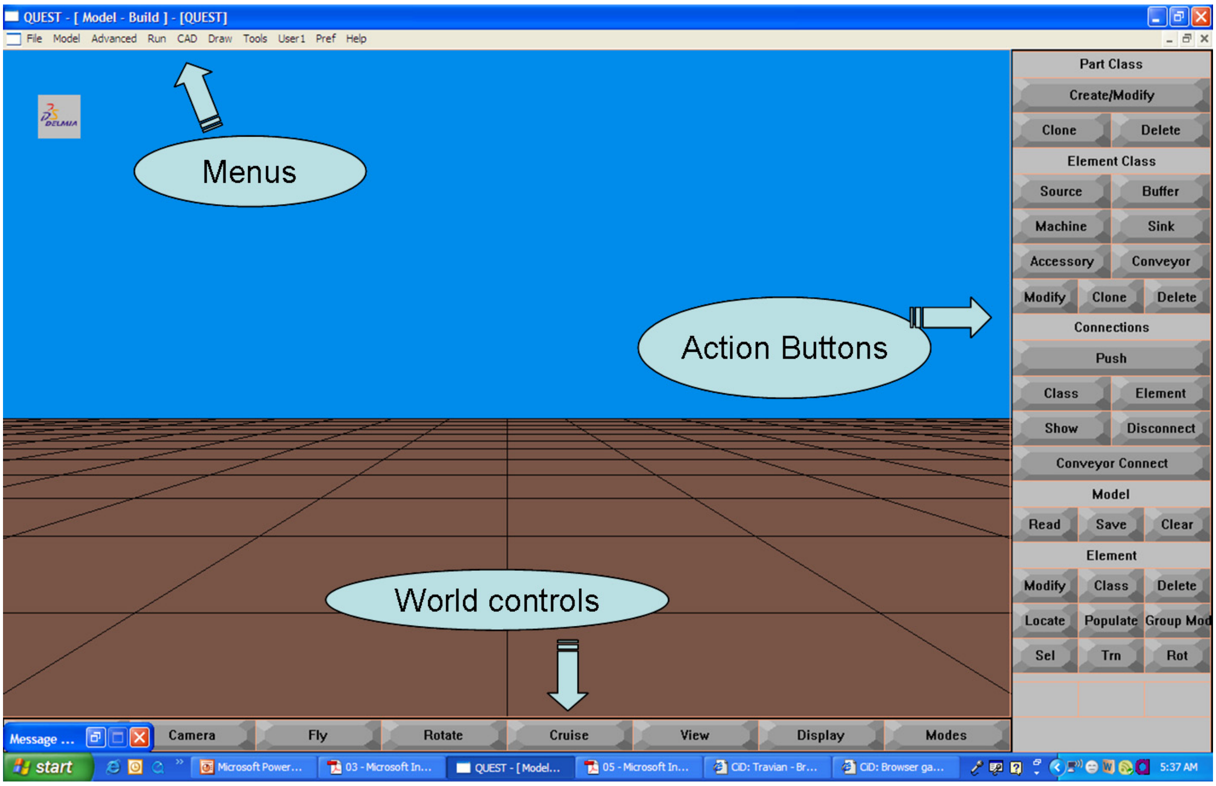


Fig. 4.1. Quest Graphical User Interface

As regards the menu features, there are ten menus (also called contexts) in QUEST. Selection of one of these menus will activate a pull-down menu, showing a series of items. For example, selecting the Model menu will show a number of items such as Build, MHS, Layout, etc.

The menus cover the following areas:

- File: The file menu contains file handling functions such as loading and saving models creating and appending libraries, and editing files.
- Model: This is the main model development menu that permits elements and element classes creation, connections and process creation.
- Advanced: This menu includes auxiliary model building items that permit creation and manipulation of groups, popups, kinematics, and display settings.
- Run: Run provides a number of controls to run and debug the simulation, and analyze the performance of the system by gathering various statistics and reports.
- CAD: CAD is used to import, create or modify the geometrical representations of the logical elements in the model. QUEST provides a set of data translators so that layouts and components may be imported from other CAD software packages.
- Draw: Draw is used for the creation or modification of 2D geometries.
- Tools: The Tools menu provides a series of functions including dimensioning, measuring, and lighting. The Windows functionality is located under the Tools menu.
- User: The User menu provides a series of user pages that can be customized. User buttons permit the duplication of any other button in the interface, and can also invoke SCL or BCL macros.
- Pref: Pref menu allows to setup preferences such as colour, button style, grid size, and level of detail. This menu thus provides options to change the appearance of QUEST.

- Help: The help menu allows to access the QUEST online help documentation and the button help.

4.3.2 MODELLING FEATURES

This paragraph will introduce the main topics concerning QUEST modelling features, in particular dealing with:

- The basic model entities (Parts, Source, Sink, Buffers, and Machines)
- The essential logic categories (process logic, route logic, request logic, part input logic, queuing logic)
- The central process types (set up process, load process, unload process, cycle process)

A QUEST model is made up of two components, the *physical model* and the *logical model*. The physical model is the 3D CAD representation of the system. On the other hand, the logical model includes two types of logical components: *parts* and *elements*.

Parts are entities that flow through the model: they are moved from element to element and processed, and they don't contain any logics. On the contrary, elements are made up of logics, attributes and geometry.

Several element types can be created in order to set up a simulation model:

Part creation and destruction elements

- Sources: Elements that create parts and release them into the simulation.
- Sinks: Elements that destroy parts.

Part storing elements

- Buffers: Elements used to store parts.

Processing elements

- Machines: Elements that process parts.

Material handling elements

- Automatic Guided Vehicles (AGV): Elements that run on predefined paths and carry parts.
- Conveyors: Elements that move parts.
- Labors: Human models that move and carry parts and carry out processes. They may also be used to model other transport elements, such as industrial robots, for example.

Other elements

- Decision points: Elements that act as sensors on conveyors or path systems of transport elements.
- Accessories: Elements that have no logics, but have a 3D CAD geometry.

Since QUEST adopts the object-class methodology to define elements, the first step in creating an element is defining an element class of the desired type, such as machine, source, buffer, etc. Once defined, the element class can be saved as an independent file and it can be retrieved within any model, so that the corresponding elements can be created in that model. This is very helpful as, in that way, a specific element type can be used over and over again.

A fundamental role in a DES model is played by the so-called "element connections": a connection is a logical link between two elements, that provides the mechanism for parts moving among elements. If no logical connection is established, parts cannot be transferred from one element to the other.

At the element class level, processes and logics can be applied. All the elements of a class will have the same logics and processes.

The term logic indicates the decision-making activities that occur at specific times on the various resources during the simulation and that govern the model's behaviour. Each element class in a QUEST model, except an accessory element, will have one or more logics assigned to it that describe the behaviour and functionality of that class. As an example, “First Available Process” is a standard process logic for assigning a cycle process to a machine, while “First In-First Out” (the well known FIFO) is a standard process logic associated with a storage element. These logics typically act on a part arriving at the particular element, or in response to it. Any number of logics can run in a model at the same time, and they belong to different categories.

The process logic controls the behaviour of parts inside an element. A process defines what happens to a part as it moves through an element; once defined, the process is associated with an element class.

Processes can be of different types:

- Cycle process
- Setup process
- Load process
- Unload process
- Repair process

On the other hand, the route logic controls the destination of parts that flow out of the current element class. Other categories of logics will be explained later.

By summarizing, the procedure to build a DES simulation model in QUEST involves the following steps:

- Set Up
- Create Part Classes
- Create Sources
- Create Processes
- Create Machines
- Create Sinks
- Create Buffers
- Connect the Elements
- Create Labor
- Associate Labor with processes
- Associate Processes to Machines
- Save the Model
- Run the Simulation

In the following paragraphs, the general features as well as the procedure to create the model components within QUEST DES software are illustrated.

4.3.2.1 PARTS

Parts are the entities that flow through the model, as they move from element to element and they are processed. In the manufacturing context, these would be the physical parts processed within the system, from the raw parts to the finished products. In DES, each event, such as a part arrival, occurs at a discrete point in time: QUEST has an internal clock that has every discrete event set in advance based on a time pointer set in the clock. Parts originate from part classes, where the attributes and 3D geometry of the parts that will be created are defined. The key difference between part classes and element classes is that, when defining a part class, the number of parts to be created is not established, since parts are only created when the simulation is actually running. The part will be created only when one part of that particular part class is required during the simulation run. Another difference is that parts do not have the ability to execute logic: they do not control the directions they take within a simulation or how they are moved. A part may have an attribute that indicates how it should be moved, but it will be the responsibility of the element doing the moving to read that attribute and act accordingly.

The path to follow in order to create part classes in a model is Model | Build | Part Class | Create/Modify, that opens the windows shown in Fig. 4.2. Attributes and 3D geometries can be defined through the associated windows, as shown in Fig. 4.3-4.4.

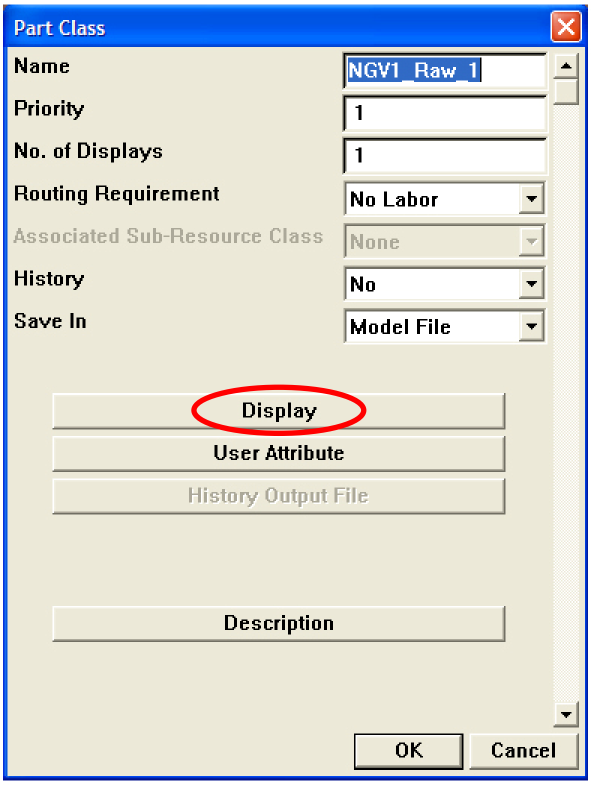


Fig. 4.2. Part class creation dialog box.

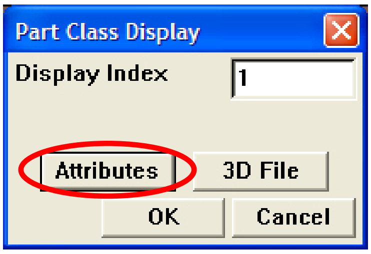


Fig. 4.3. Part class display options.

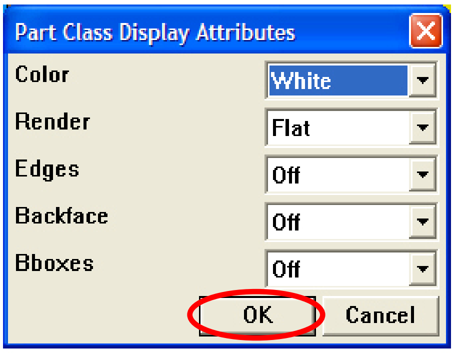


Fig. 4.4. Part class attributes dialog box.

4.3.2.2 ELEMENTS

SOURCES

Sources are the elements designed to create the parts that will be processed by the other model elements. They represent the point-of-entry of parts into a model. They are flexible elements that offer a wide range of options. The characteristics of a source may be modified by following the Model | Build | Element Class | Source path. The dialog box for creating and modifying the source characteristics is shown in Fig. 4.5.

Max Part Count allows to set the maximum number of parts that a source can produce during a single run of the model. Start Offset allows to set a time delay on the start of the parts production. Part Creation Mode sets the manner in which part creation is controlled. Output Type sets the manner in which parts are dispatched from the source. The Initial Stock button sets the numbers and classes of parts that are already present in the source when the model run begins. IAT (Inter Arrival Time) sets the time between part creations. Lotsize sets the number of parts arriving simultaneously. Part Fractions sets the proportions of each part class that the source will create. Finally, Process Logic allows to specify a process logic of a source according to one of four options as shown in Fig. 4.6.

New customized process logics can be defined through SCL programming (User Func option) or by writing a proper file defining what the source must create and when (File Based Source Logic option). For the latter purpose, a new file for Part Creation should be created within the File | Edit file | Schedule folder. Fig. 4.7 shows an example of File based source logic. In the first column, the name of the part class to be created should be inserted. In the second column the creation time, which represents the time after which the source creates the new type of part, is indicated (in this case it is null). Finally, the last column is used to introduce the value of the lot size that has to be produced.

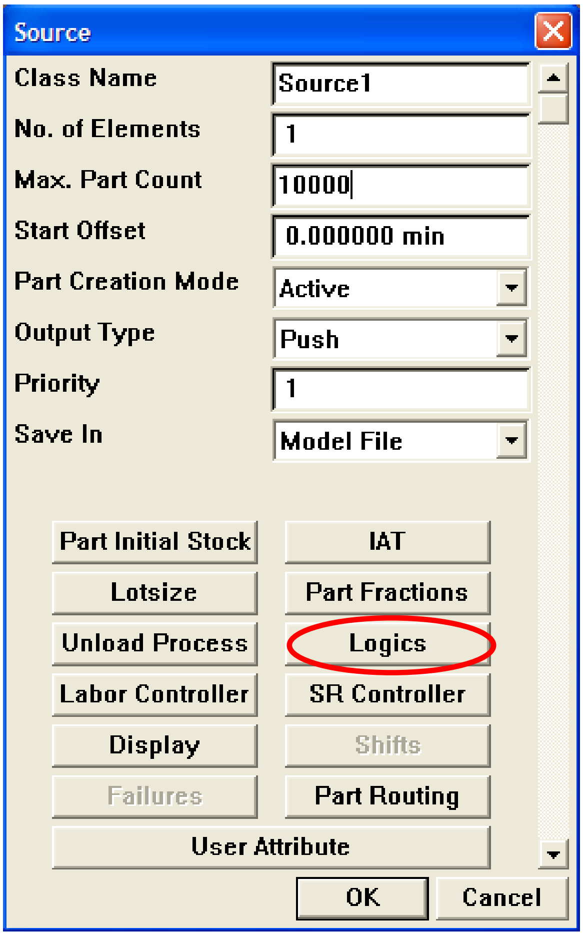


Fig. 4.5. Source creation dialog box.

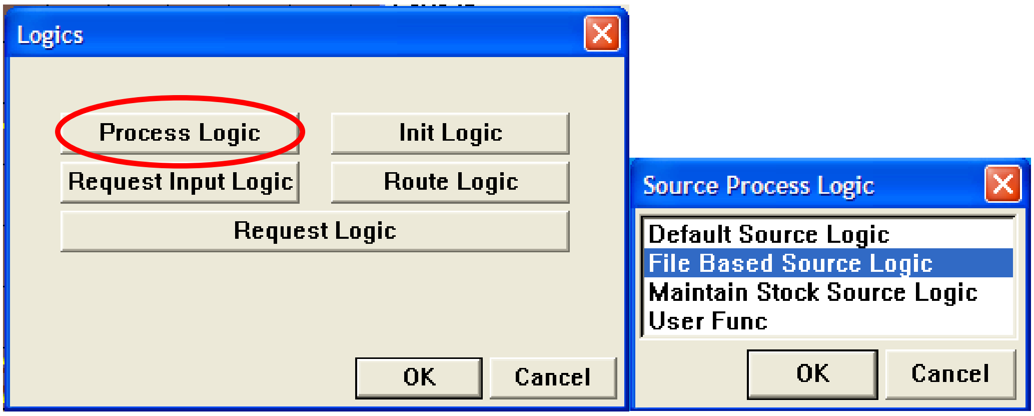


Fig. 4.6. Process logic dialog box.

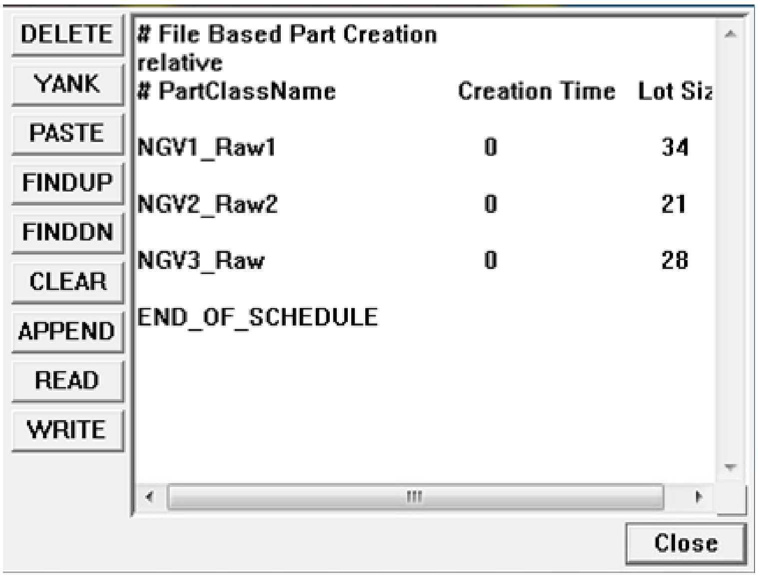


Fig. 4.7. Example of file for part creation.

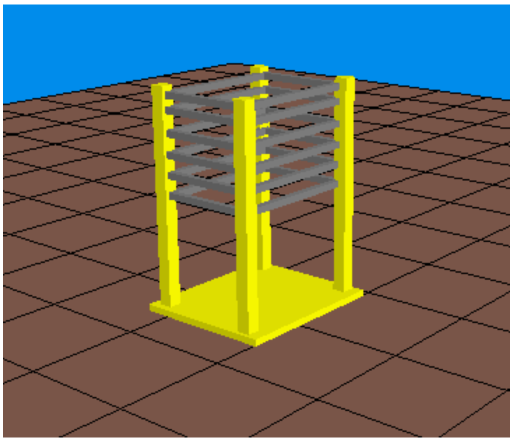


Fig. 4.8. Default source 3D file.

SINKS

Sinks are designed to destroy parts at the end of the production process. For this reason, they can have inputs but no outputs. Although the parts are destroyed in the sink, all the statistics related to these parts are preserved by the software and may be accessed at any time during or after the simulation run. The characteristics of a sink can be modified by selecting Model | Build | Element Class | Sink. A dialog box appears that allows the selection of an existing sink class by name or the creation of a new sink class. Fig. 4.9 shows the window for the sink parameters modification, while Fig. 4.10 shows the default sink geometry.

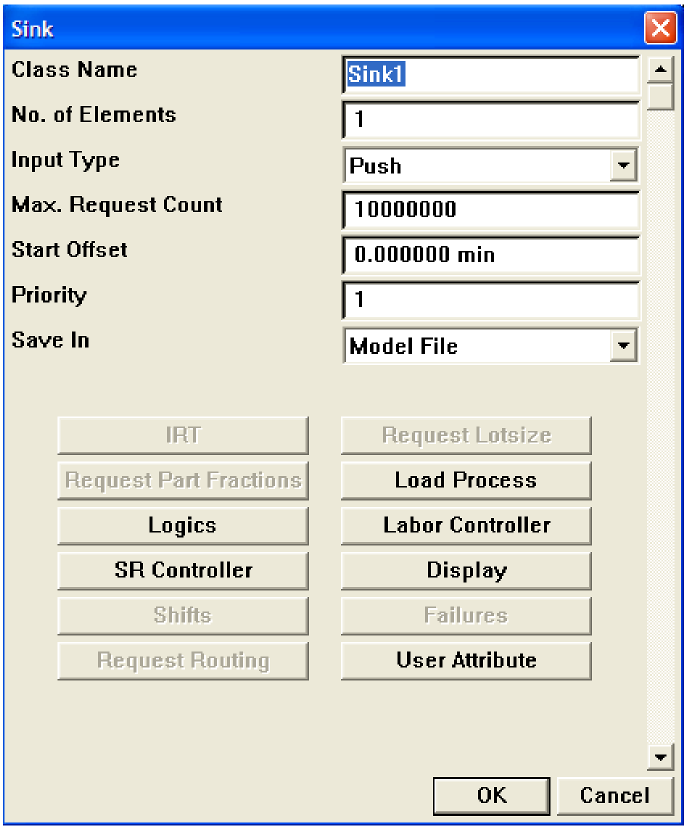


Fig. 4.9. Sink creation dialog box.

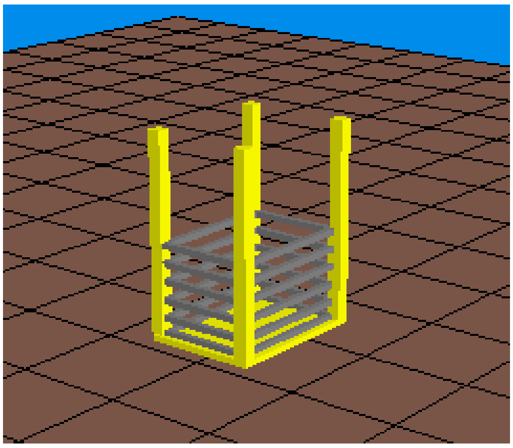


Fig. 4.10. Sink default geometry.

MACHINES

Machines represent the system elements responsible for processing parts. The characteristics of a machine may be modified by selecting Model | Build | Element Class | Machine, that opens the dialog box shown in Fig. 4.11. A number of parameters can be modified. The input type of the machine can be toggled to either Push or Pull, as well as the output type. The No. of processes can be set as machines are capable of performing more than one operation, although not simultaneously. An Unload Process can be assigned to the machine. The Cycle Process button allows to define and assign cycle processes to the machine class. The Setup Process buttons allows to assign setup processes between any two-cycle processes. Most important is the machine Logics button, that allows to influence the behaviour of a machine by changing the rules through which the machine operates. This can involve selecting from one of the many available standard behaviors or specifying a user defined function, written in SCL, that performs the required operations. The Process Logic controls the behavior of a part inside the machine. Many options are available such as First Possible Process, Percentage Process, Cyclic Process, Sequence Process, Precedence Process, User Func(define your own logic to govern the setting of process to a machine).

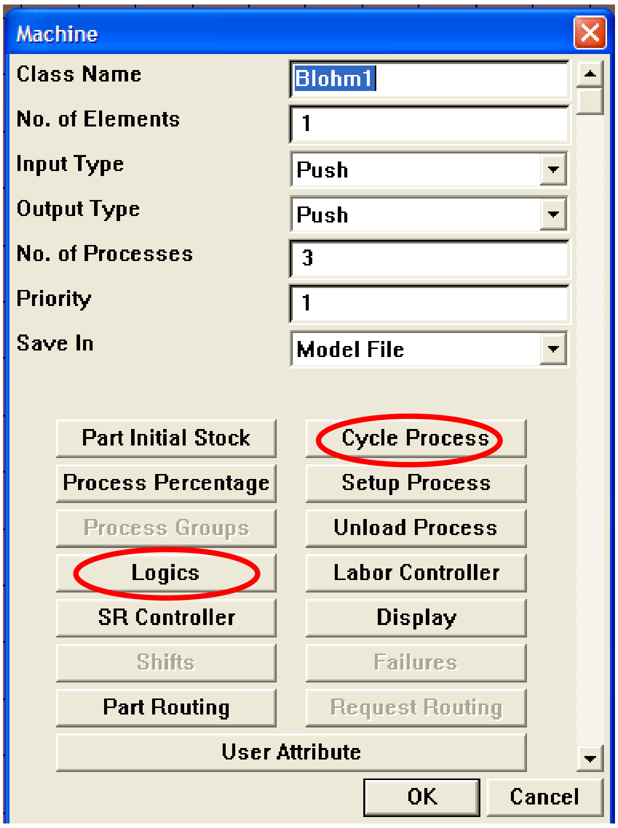


Fig. 4.11. Machine creation dialog box.

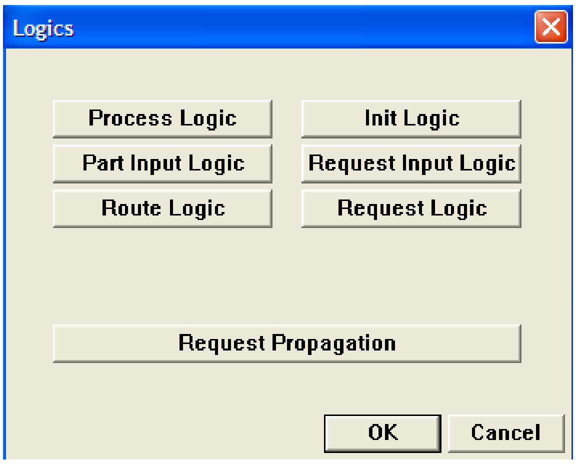


Fig. 4.12. Logics dialog box.

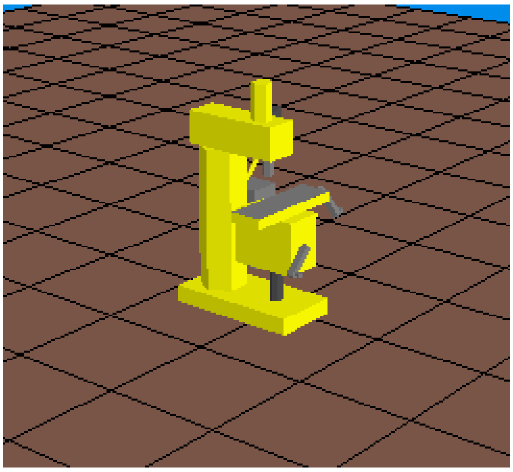


Fig. 4.13. Machine default geometry.

BUFFERS

Buffers represent the locations where parts are stored or where they queue before accessing to other resources such as machines. A buffer might thus represent a storage location in a warehouse, the buffer feeding parts into a machine, etc. A new buffer may be created or an existing one modified by selecting Model | Build | Element Class | Buffer, as shown in Fig. 4.14. Many options can be used to define the buffer's behaviour. Input Type is employed to specify the method by which parts should enter the Buffer, that can be either push or pull. On the other hand, Output Type is used to specify the method by which parts should exit the buffer. Capacity Type defines the maximum number of parts that the buffer can hold at the same time. Load/Unload Process sets the manner in which parts are loaded into or unloaded from the buffer. Buffer Logics influence the behaviour of a buffer by changing the rules through which the buffer operates. This can involve selecting from one of the many available standard behaviours or specifying a user-defined function, written in SCL, that performs the required operations. Process Logic controls parts behaviour after entering the buffer. Queue Logic allows to specify the order in which parts are passed out of the buffer (e.g. FIFO).

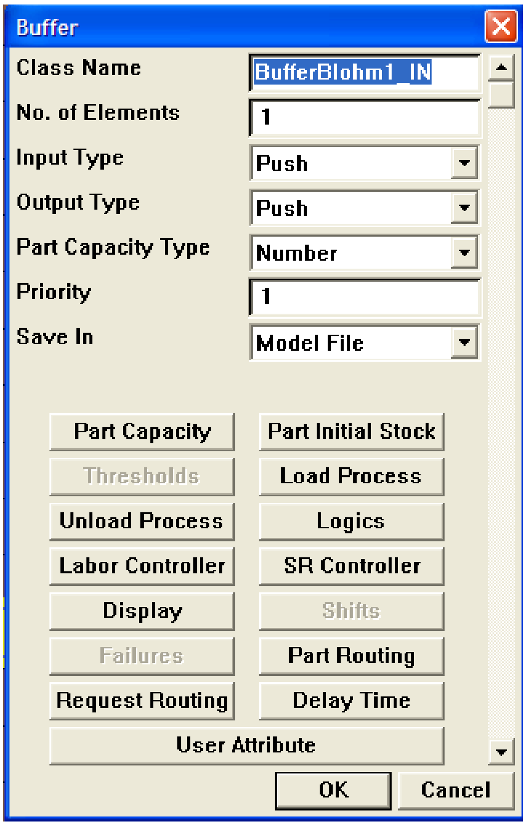


Fig. 4.14. Buffer creation dialog box.

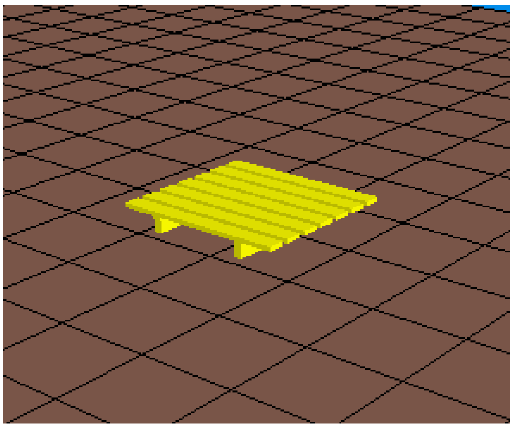


Fig. 4.15. Buffer default geometry.

LABORS

Labors are the element that move around the system, satisfying process requirements, transporting parts, and loading and unloading parts at various locations. Labors can be located on labor path systems and move on their segments as an AGV, or can create their own paths so that they can move to any labor point, as required. Defining a labor class that defines their basic characteristics and behaviour is the first step to create creates individual labor elements. All the labors belonging to the same class have similar characteristics and behave the same way. However, logics may be written for the labors so that each element within the class behaves differently. The behaviour of labors can be modelled to work under a controller or on their own without a controller. In order to model labors without a controller, custom labor process logics must be written.

The labor controller is the main decision making element. In a model there may be many laborers, decision points, and elements requiring labor, and the controller coordinates the behavior of these different elements to accomplish the set of tasks. The behavior of the controller is defined by its process logic and due to the coordination and decision-making nature of the controller, this process logic is complex compared to other elements.
To create the labor it is first necessary to create a Labor Controller, then the labor can be created through the path Model | MHS | MHS Element | Labor, as shown in Fig. 4.16- 4.17.

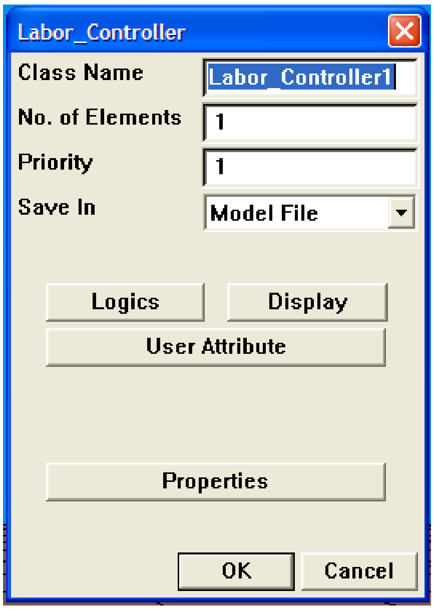


Fig. 4.16. Labor controller creation dialog box.

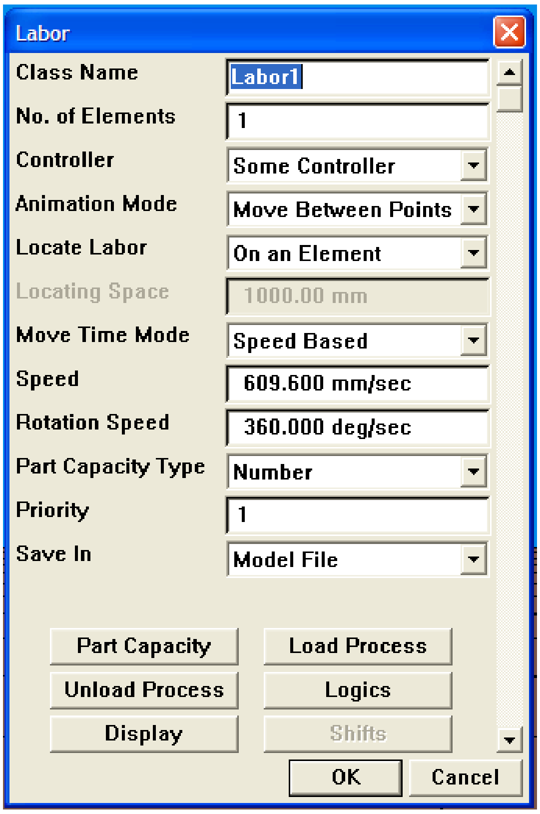


Fig. 4.17. Labor creation dialog box.

4.3.2.3 PROCESSES

Processes define what happens to a part as it moves through an element. There are a number of different processes that can be assigned to different QUEST elements. Once defined, the process is associated with an element class, thus giving that element class the possibility to carry out that process. Whether the specified process will be carried out or not, depends on the element classes logic.

The most common processes include:

– Setup Process.
  This process represents the setup of a machine between operations. It is generally executed at the beginning of a batch of parts. A setup process can specify requirements for parts, AGV, labor, and products that may result from the process.
– Load Process.
  This defines the process of loading each part into the element for processing. Load processes are commonly used within a batch, whereas a setup process will be used to change a machine between two different batches.
– Unload Process.
  This defines the process of removing a part from an element after being processed.
– Cycle process.
  This process is carried out by a machine to process one or many parts. A cycle process can be defined by a set of requirements (parts, resources, labours, AGV, etc.), a cycle time and a set of products.
– Repair Process.
  This is the process that determines how long it takes to repair an element after a break down. This is a special type of process that can be run at any time when an element fails.

As with a setup process there may be requirement for repair operators and tools, and there will be a repair time once the repair process begins.

The typical procedure to create a cycle process involves the following steps. The Model | Process | Cycle path allows to open a window for the cycle process definition, as in Fig.4.18. The cycle process parameters can be defined through the dialog boxes shown in Fig. 4.19-4.21, where part requirements, cycle time and products are indicated.

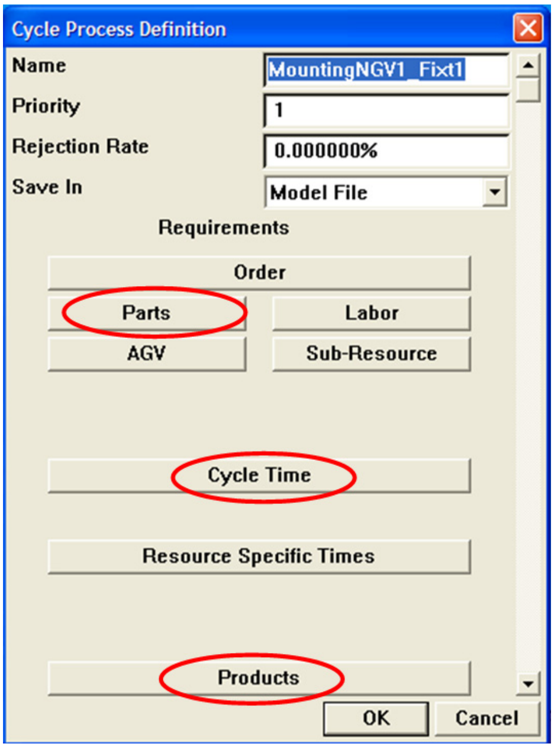


Fig. 4.18. Cycle process dialog box.

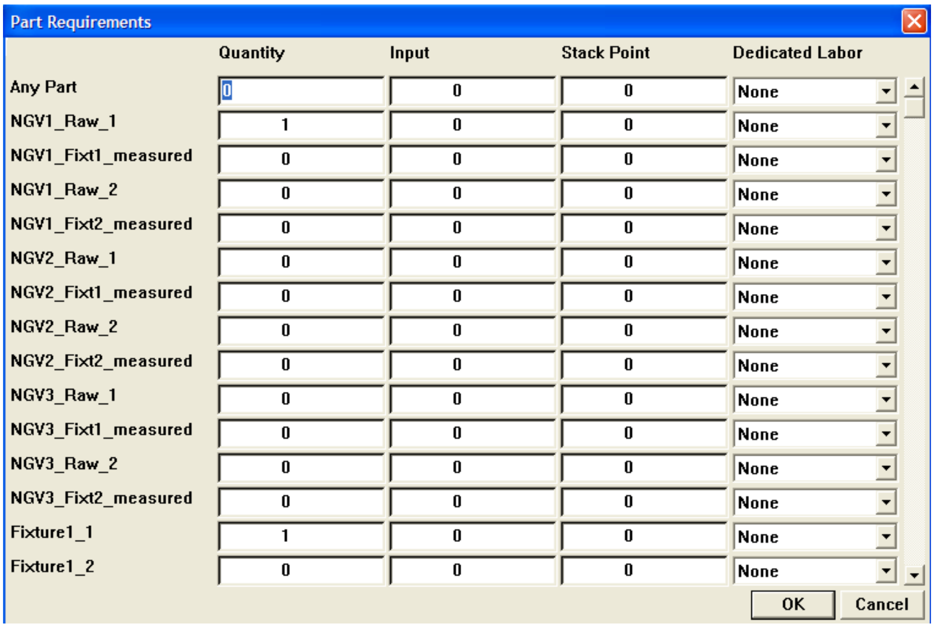


Fig. 4.19. Part requirement definition.

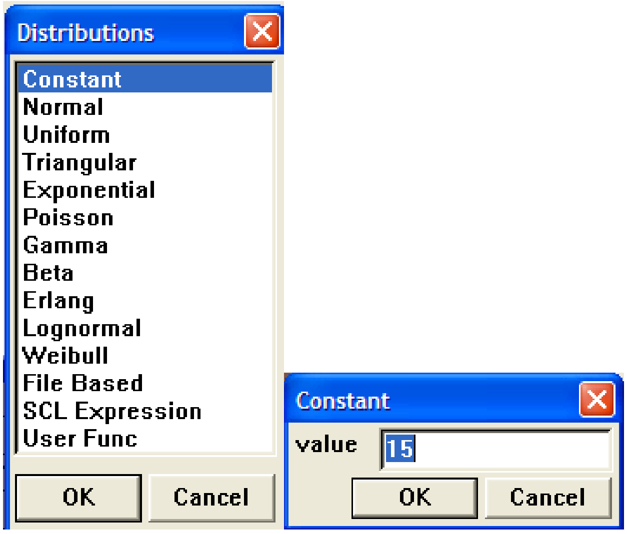


Fig. 4.20. Cycle time definition.

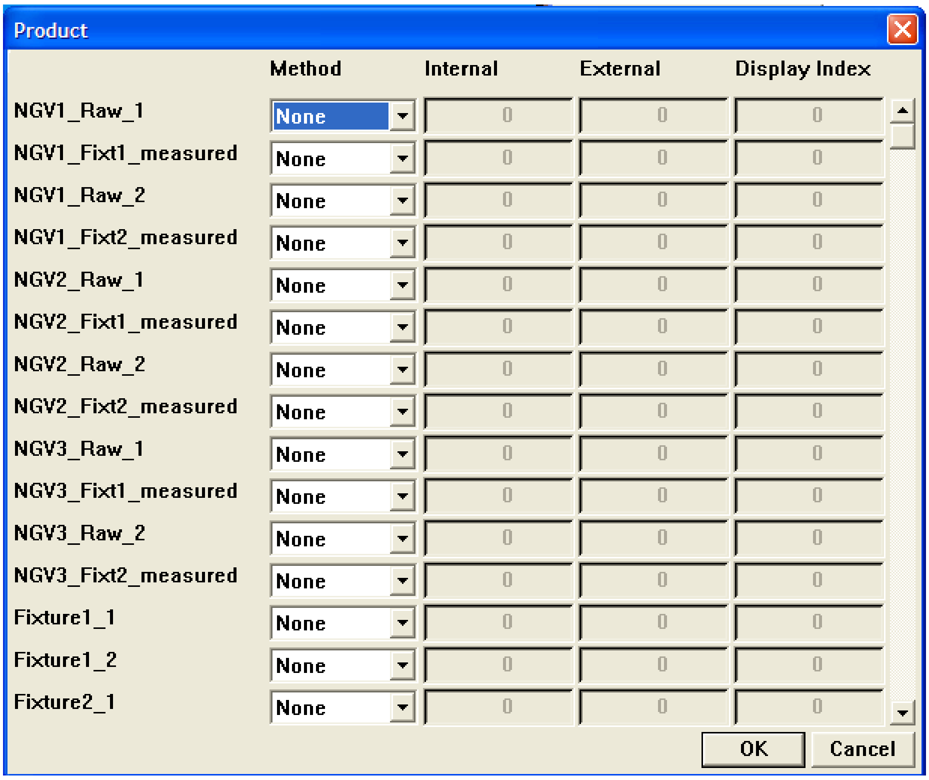


Fig. 4.21. Product specification dialog box.

4.3.2.4 Logics

Each element class in a QUEST model (except accessory elements) will have one or more logics assigned to it that describe its behaviour. The main logics in a QUEST Model are the Process Logic and the Route Logic. Usually, the process logics of elements are executed when the part is on the input side of an element, and the route logics when the part is on the output side. In general terms, the logics associated with an element define which process is to be run. Logics also define rules regarding the movement and order of parts.

The process logic controls the behaviour of an element when a part has entered the element. In most elements, the process logic is responsible for requesting and obtaining a part and then processing it at the element. Most element classes in QUEST have a default process logic. The process logics of all element classes are running all the time, although they may not actually be doing anything other than waiting for a part or a command.

The route logic defines the parts flow between elements, i.e., to which output, and hence, to which element, a part is to go after being processed.

Other relevant logics are the request logic, that controls the flow of requests between elements in a Pull model, the part input logic, that controls the arrival of parts at the element when class connections are used, the queuing logic, that determines the rules for parts that leave the buffer (For example, the First-In-First-Out (FIFO) logic).

Moreover, user-defined logics can be defined when the combination of standard processes and logics provided through the button interface are not adequate to define the required behaviour. In this case, the logic links to a user-written function in QUEST's Simulation Control Language (SCL). SCL is a custom simulation language with a wide range of functionalities to program logical situations in a simulation model. User-developed SCL can be used along with standard processes defined through the user interface. Alternatively one can define functionality completely within SCL without reference to the standard processes or attributes that have been defined through the user interface in QUEST. While most situations are covered by the standard logics and processes provided in QUEST, you may find that certain modelling situations will require the use of custom SCL logics.

The basic structure of SCL is similar to other structured programming languages. Procedures and routines are defined with a name, variables, and begin/end statements. The procedure is then associated with a particular logic, for example the process logic of the decision point element. In this case the logics are run every time a part arrives at the decision point.

The SCL commands are specialized to work in a simulation environment. It employs IF/ THEN/ ELSE constructs, typical of general programming languages. SCL provides a rich set of general programming functions allowing to model almost any situation.

4.3.2.5 CONNECTIONS

Connections in a QUEST model represent the links between the various elements. A part cannot move between two elements that do not have a connection. Once the elements in a model are connected, part transfer is governed by the logics of the element classes.

Most elements have at least one input and one output connection, since parts move to the element through an input connection, and move to another connected element through an output connection. Exceptions are represented by sources and sinks that have only output and input connections respectively. This is due to their function of creating parts in the case of a source and destroying parts in the case of a sink.

Connection types can be either push or pull. Within a push connection, the part will move automatically once it is released by the upstream element. On the contrary, a pull connection requires the downstream element to request the part from the upstream element. Only after the request is received and processed the part moves forward through the model.

Element connections are shown graphically with arrows starting from the input element and pointing to the output element, as shown in Fig. 4.22. White arrows are used for element connections and purple arrows are used for class connections.

The path Model | Build | Connections | Element must be followed to create connections among elements.

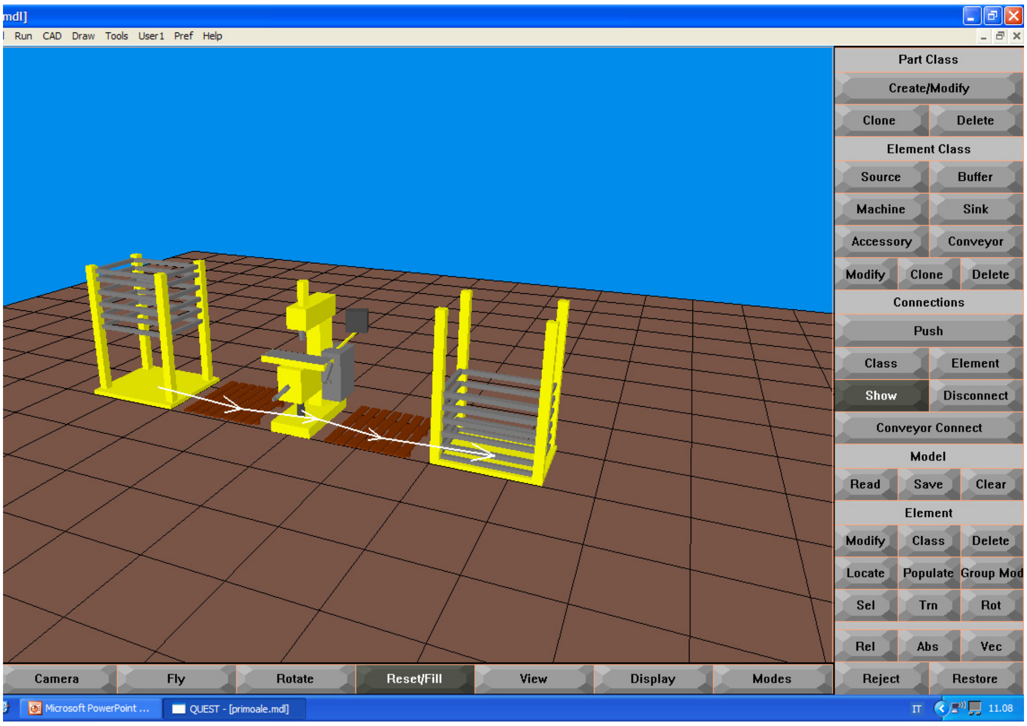


Fig. 4.22. Connections among the model elements.

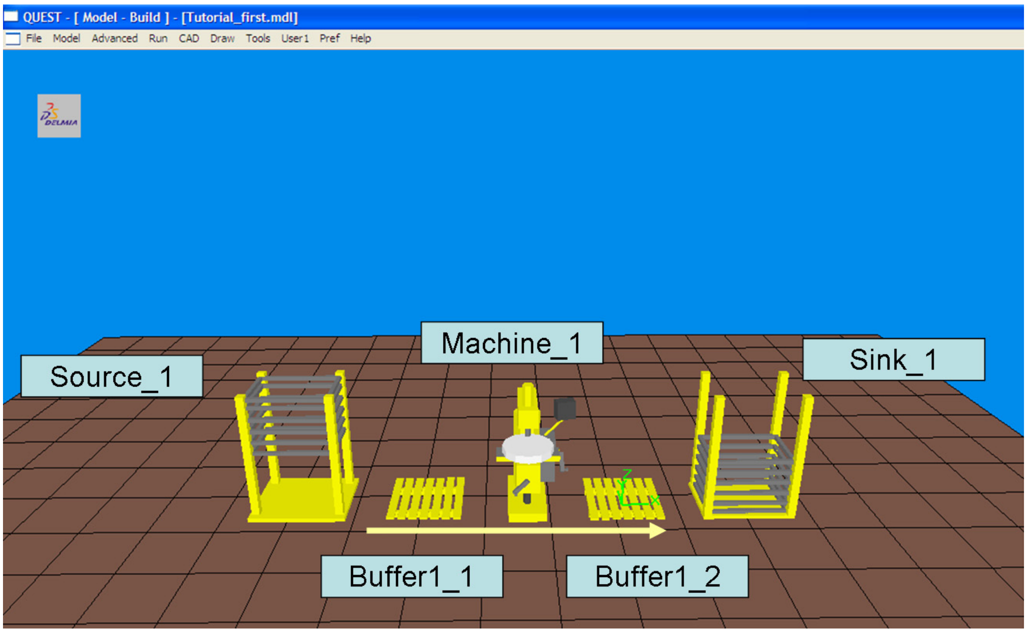


Fig. 4.23. Final DES model.

4.4 Simulation Run: Results Reporting

Once a system has been modelled, simulation must be run to analyse the system's behaviour. This paragraph illustrates how to run a model and obtain result information in form of numerical reports and charts.

Through the Run | Simulation | Modes path, simulation modes can be defined, as in Fig. 4.24. Then, the Model | Run | Simulation | Run path must be followed to define parameters such as time for the simulation run, Fig. 4.25.

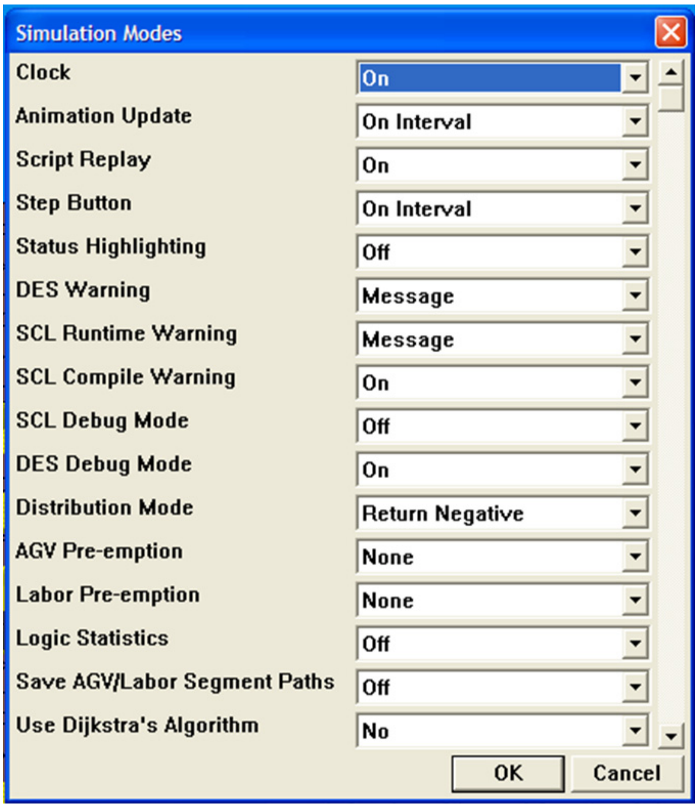


Fig. 4.24. Simulation modes definition.

Fig. 4.25. Simulation run parameters.

To obtain the results from simulation runs, QUEST provides several tools to output data and statistics in both numerical and graphical form.

4.4.1 Numerical Reports

Reports can be created for a single element or part class as well as for the entire model. In case of a single element, the Run | Single Run Output | Element button is used to show the run statistics for the element. This button will display the statistics gathered during the most recent simulation run for that element in a dialog box as that represented in Fig. 4.26.

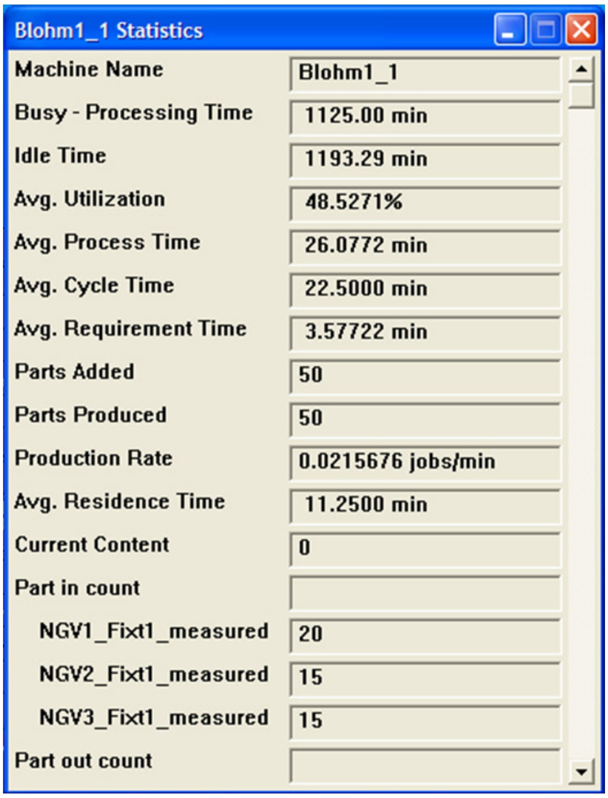


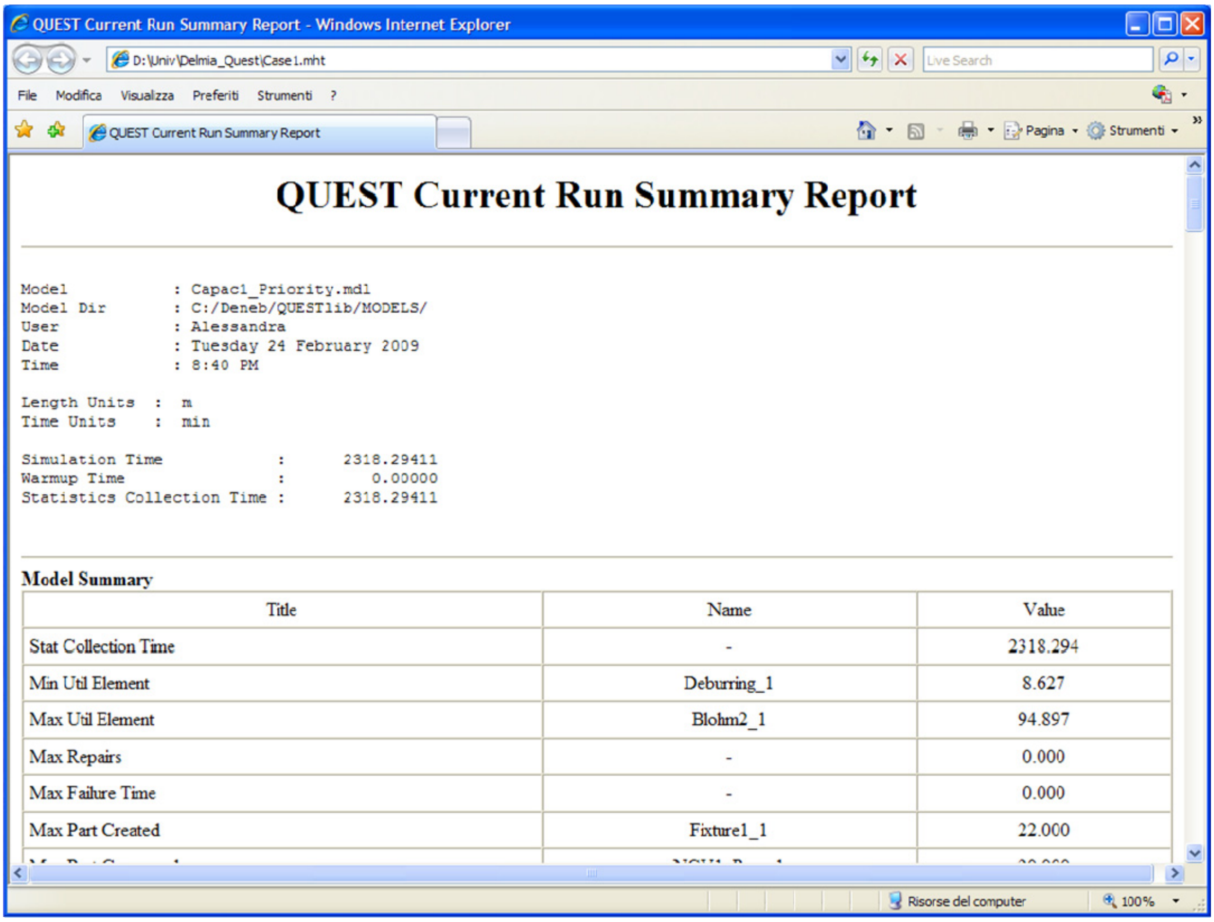
Fig. 4.26. Statistics for a single element.

The Run | Single Run Output | Part Class button will display the statistics gathered during the most recent simulation run for a selected part class. For each class chosen, the run statistics dialog box will appear.

Another option is the Custom Report, that allow to define a set of run statistics of interest, and generate a report of those statistics for all relevant elements in the model. When this button is selected a dialog box appears offering a list of statistical quantities that may be either enabled or disabled for report generation. Once defined, the system writes a report to the specified file containing the selected statistics from the most recent run for all elements for which the statistics are relevant.

In order to obtain statistics on the entire model, two options are available: Display Mode and File Mode.

When the output mode button is set to display it produces a dialog box reporting several general statistics of the entire model for the most recent run. When the output mode toggle button is set to file, this button writes a summary for elements to the specified file. If you specify a file name with the .html extension, the model statistics will be written to an HTML file that is viewable using any standard web browser. The HTML version of the file provides better format for the file than the ASCII format, with tags and tables available to quickly locate and select entities, as shown in Fig. 4.27.



QUEST Current Run Summary Report

```
Model          : Capaci_Priority.mdl
Model Dir      : C:/Deneb/QUESTlib/MODELS/
User           : Alessandra
Date           : Tuesday 24 February 2009
Time           : 8:40 PM

Length Units  :  m
Time Units    :  min

Simulation Time            :     2318.29411
Warmup Time                :        0.00000
Statistics Collection Time :     2318.29411
```

Model Summary

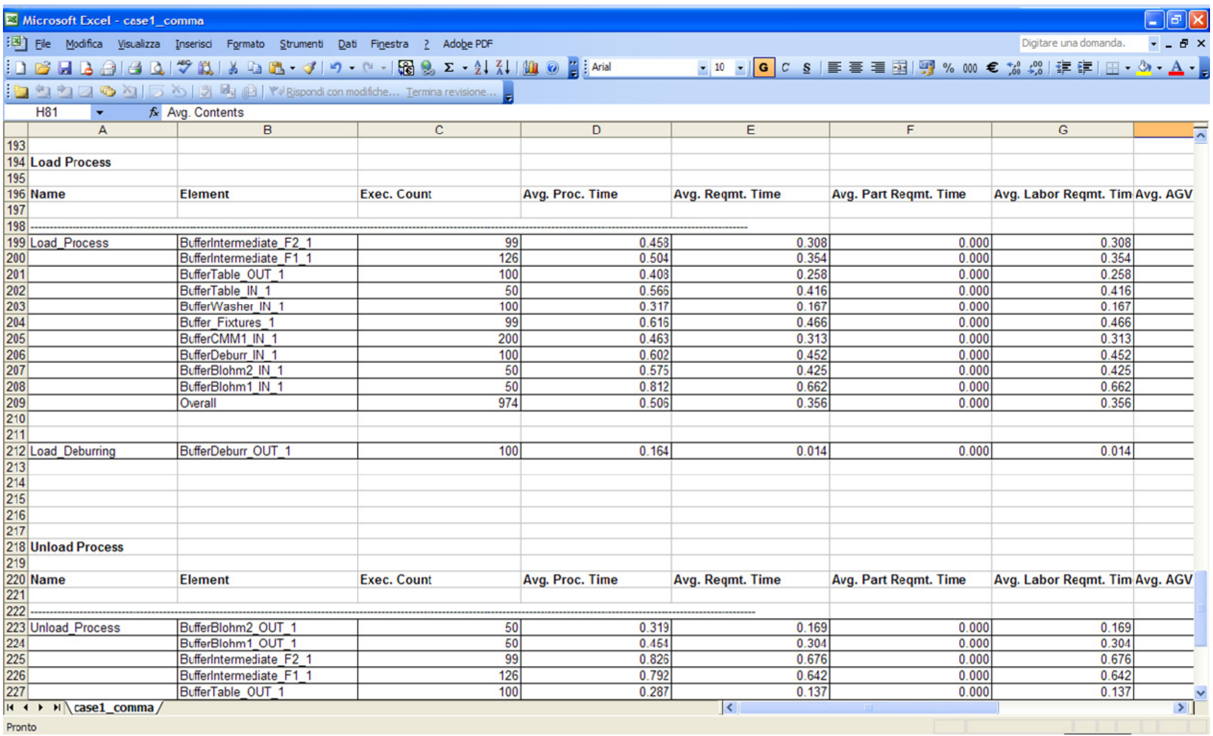
Title	Name	Value
Stat Collection Time	-	2318.294
Min Util Element	Deburring_1	8.627
Max Util Element	Blohm2_1	94.897
Max Repairs	-	0.000
Max Failure Time	-	0.000
Max Part Created	Fixture1_1	22.000

Fig. 4.27. Fig. Report: Display Mode

When the output mode is set to File, the following options can be selected:

– Formatted - This selection doesn't change the format of the output file, format remains the same.
– Comma Delimited - This selection separates words and numbers by a comma.
– Tab Delimited - This selection separates words and numbers by a tab space.

The file mode can be employed in order to import a numerical report in Excel software, as shown in Fig. 4.28



	A	B	C	D	E	F	G	H
193								
194	**Load Process**							
195								
196	**Name**	**Element**	**Exec. Count**	**Avg. Proc. Time**	**Avg. Reqmt. Time**	**Avg. Part Reqmt. Time**	**Avg. Labor Reqmt. Tim**	**Avg. AGV**
197								
198	----------							
199	Load_Process	BufferIntermediate_F2_1	99	0.453	0.308	0.000	0.308	
200		BufferIntermediate_F1_1	126	0.504	0.354	0.000	0.354	
201		BufferTable_OUT_1	100	0.403	0.258	0.000	0.258	
202		BufferTable_IN_1	50	0.566	0.416	0.000	0.416	
203		BufferWasher_IN_1	100	0.317	0.167	0.000	0.167	
204		Buffer_Fixtures_1	99	0.616	0.466	0.000	0.466	
205		BufferCMM1_IN_1	200	0.463	0.313	0.000	0.313	
206		BufferDeburr_IN_1	100	0.602	0.452	0.000	0.452	
207		BufferBlohm2_IN_1	50	0.575	0.425	0.000	0.425	
208		BufferBlohm1_IN_1	50	0.812	0.662	0.000	0.662	
209		Overall	974	0.506	0.356	0.000	0.356	
210								
211								
212	Load_Deburring	BufferDeburr_OUT_1	100	0.164	0.014	0.000	0.014	
213								
214								
215								
216								
217								
218	**Unload Process**							
219								
220	**Name**	**Element**	**Exec. Count**	**Avg. Proc. Time**	**Avg. Reqmt. Time**	**Avg. Part Reqmt. Time**	**Avg. Labor Reqmt. Tim**	**Avg. AGV**
221								
222	----------							
223	Unload_Process	BufferBlohm2_OUT_1	50	0.319	0.169	0.000	0.169	
224		BufferBlohm1_OUT_1	50	0.454	0.304	0.000	0.304	
225		BufferIntermediate_F2_1	99	0.826	0.676	0.000	0.676	
226		BufferIntermediate_F1_1	126	0.792	0.642	0.000	0.642	
227		BufferTable_OUT_1	100	0.287	0.137	0.000	0.137	

Fig. 4.28. QUEST report imported in Excel.

Finally, the Run | Multi Run page allows to output data from a batch run, that refers to more runs of the simulation model.

4.4.2 Graphical Reports: Charts and Diagrams

QUEST reporting features include the possibility to generate graphical reports such as charts and diagrams.

Pie Charts can be created for element utilization, part count, or user-defined parameters by writing an SCL expression.

To create a new utilization pie chart for an element, the element must be selected. After that, a chart definition dialog box is displayed that allows entry of the chart attributes. If the default title is left unchanged the element name will be added to the title when it is displayed, otherwise the text entered will be used. The text color, 3D effects, and interval at which the display is to be updated may also be specified. You will then select a position for the chart by clicking on a point in a 2D window with the mouse. The states shown on the chart are idle time, busy time, blocked time, failed time, and off-shift time, as shown in Fig. 4.31.

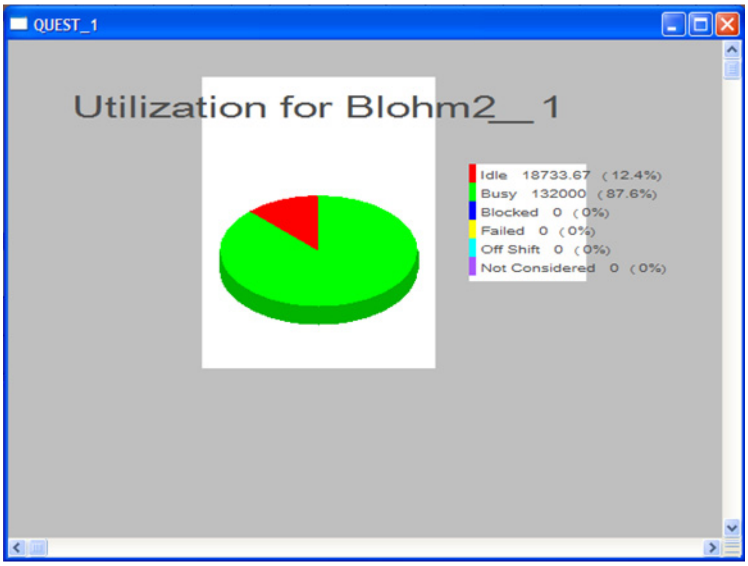


Fig. 4.29. Utilization pie chart for an element.

Other types of charts that can be created are histograms, time series, bar charts and group bar charts, and SCL charts. In order to create an SCL chart, an SCL file must be written including an initialization procedure and an update procedure, as shown in Fig. 4.30.

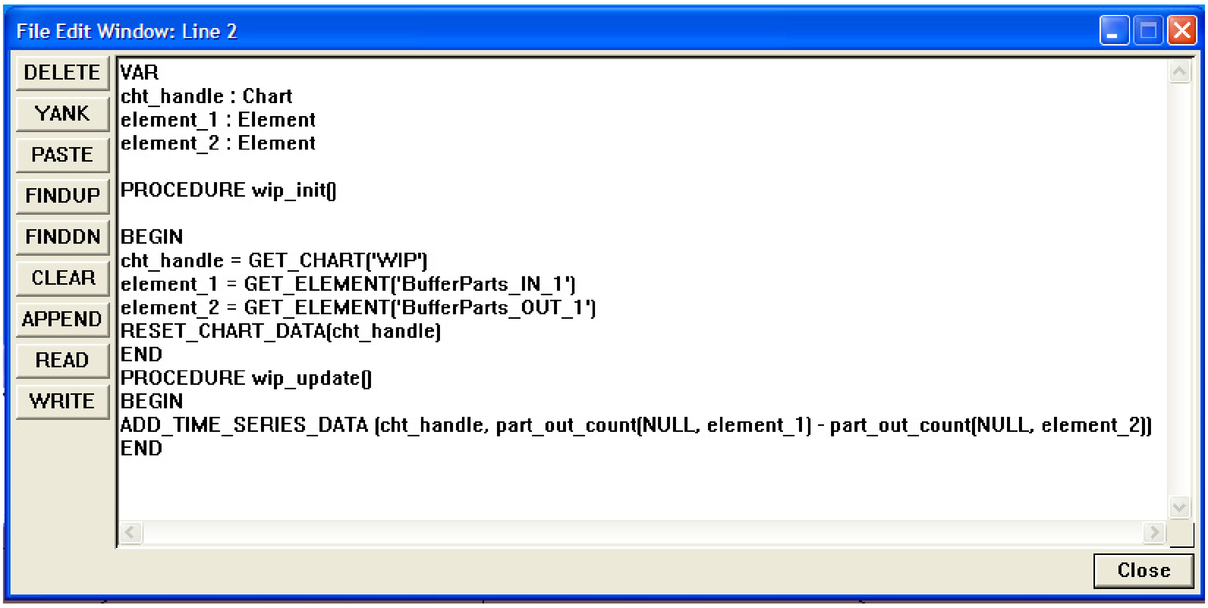


Fig. 4.30. Example of SCL file for chart creation.

CHAPTER 5

APPLICATION OF DISCRETE EVENT SIMULATION TO A MANUFACTURING CELL

5.1 INTRODUCTION

In this chapter, the application of Discrete Event Simulation (DES) for the study of a robotic manufacturing cell is presented. DES helps the modeling, analysis and simulation of production flow and processes in order to evaluate the performance of the manufacturing cell.

5.2 THE MANUFACTURING CELL

The manufacturing cell considered for this simulation application is an existing manufacturing cell located at the facility of the aircraft engine manufacturing company Avio Spa, Pomigliano d'Arco, Naples.

The manufacturing cell examined in the current simulation activity is dedicated to the performance of two-phase grinding operations 1 stage of turbine vanes called NGV1.

The model presented in this report is built on the basis of the knowledge on layout, processes and logics governing the manufacturing cell, acquired through interaction between the University of Naples (Department of Materials and Production Engineering) and Avio SpA.

In the following paragraphs, a description of the cell is given in terms of involved components, layout, parts and processes.

5.2.1 LAYOUT AND COMPONENTS

The manufacturing cell consists of the following elements:

- 1 Grinding Machine Tool (Makino)
- 1 Coordinate Measuring Machine (CMM)
- 1 Washing Station
- 1 Deburring Station
- 1 Air Cleaning Station
- 1 Rotating Table (where a human operator mounts the vanes on the proper fixtures before each manufacturing cycle, both for first and second phase grinding)

Moreover, a number of buffers is included in the cell, in order to collect the available fixtures, the vanes mounted on fixtures, or the vanes entering and exiting the cell.

The handling devices are represented by two robots, one dedicated to loading/unloading operations on the grinding machine, the other dedicated to the transfer of parts among machines throughout the manufacturing cell. A scheme of the cell is shown in Fig. 5.1, while its components are summarised in Table 5.1.

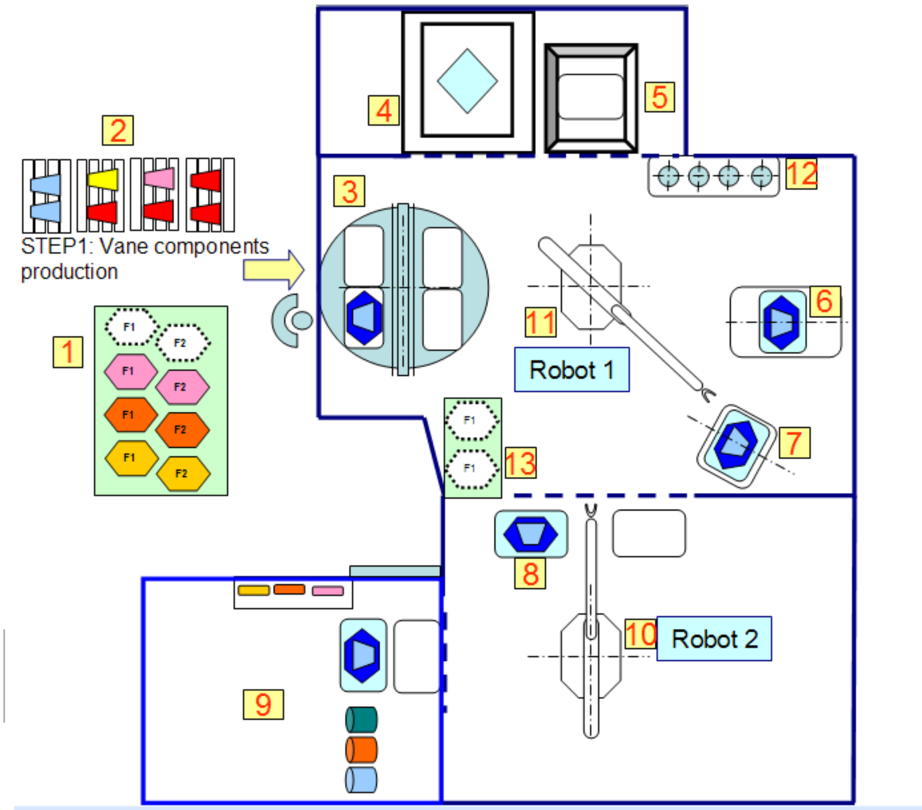


Fig. 5.1. Starting scheme of the manufacturing cell layout.

N.	MANUFACTURING CELL COMPONENT
1.	Fixtures Buffer
2.	Input Vanes Buffer
3.	Vane/Fixture Assembly Rotating Table
4.	CMM – Coordinate Measuring Machine
5.	Washing Station
6.	Automatic Deburring Station
7.	Air Cleaning Station
8.	Grinding Buffer (N.2 Positions)
9.	Grinding Machine
10.	Grinding Robot
11.	Handling/Deburring Robot

12.	Tooling Storage
13.	Intermediate Buffer

Table 5.1. Manufacturing cell components.

Fig. 5.2-5.3 show the grinding machine tool employed in the manufacturing cell: it is a Makino G5 grinding machine with a robot dedicated to part loading/unloading on the machine.

Fig. 5.2. Makino G5 grinding machine.

Fig. 5.3. Robot loading a part on the Makino G5 grinding machine.

5.2.2 Parts and Processes

The described cell is dedicated to the production of one type of turbine vanes, called NGV1, which is part of a kit composed by different types of vanes (34 NGV1 vanes for each kit). The production cycle of these vanes requires a number of subsequent operations, including not only the manufacturing processes, but also transporting tasks (e.g. the movement of parts and fixtures throughout the cell), as reported in the following Table 5.2.

Sl.No	Process	Sequence of Operation	Automated / manual	Component Position	Cycle time (min)
1	Material handling	Labor moves the fixture (phase 1) to the rotating table	manual	Labor	0.6
2	Material handling	Labor moves the raw vane to the rotating table	manual	Labor	0.6
3	Fitting up/Mounting	Loading of part into grinding/measurement fixture	manual	Rotating Table	5
4	Material handling	Handling Robot moves part to the CMM machine	automated	Handling Robot	0.5
5	Measuring	Measuring of part before machining	automated	CMM	4
6	Material handling	Handling Robot moves part to the grinding machine input buffer	automated	Handling Robot	0.5
7	Material handling	Grinding Robot moves part from the input buffer to the grinding machine working table	automated	Grinding Robot	1.5
8	Grinding (phase 1)	GRINDING trailing edge surfaces	automated	Grinding Machine	30
9	Material handling	Grinding Robot moves part from the grinding machine working table to the output buffer	automated	Grinding Robot	1.5
10	Material handling	Handling Robot moves part to the air cleaning station	automated	Handling Robot	0.5
11	Air cleaning	Air cleaning	automated	Air Cleaning Station	2
12	Material handling	Handling Robot moves part to the deburring station	automated	Handling Robot	0.5
13	Material handling	Handling Robot picks a deburring instrument from the tooling storage	automated	Handling Robot	0.5
14	Deburring	Handling Robot performs Deburring of edges on the machined surfaces	automated	Deburring Station	5
15	Material handling	Handling Robot returns the deburring instrument back to the tooling storage	automated	Handling Robot	0.5

16	Material handling	Robot moves part to the washing machine	automated	Handling Robot	0.5
17	Washing	Part Washing to remove chips and oil/emulsion film	automated	Washing Machine	3
18	Material handling	Robot moves part to the CMM machine	automated	Robot	0.5
19	Measuring	Measuring of machined surfaces in the grinding machine	automated	CMM	10
20	Material handling	Robot moves part fitted to the rotating	automated	Robot	0.5
21	Dismounting	Dismounting of part and fixture assembly	manual	Rotating Table	1.5
22	Material handling	Labor moves the fixture (phase 1) to the storage	manual	Labor	0.6
23	Material handling	Labor moves the fixture (phase 2) to the rotating table	manual	Labor	0.6
24	Mounting	Loading of part into grinding/measureme nt fixture	manual	Rotating Table	3
25	Material handling	Handling Robot moves part to the CMM machine	automated	Handling Robot	0.5
26	Measuring	Measuring of part before machining	automated	CMM	4
27	Material handling	Handling Robot moves part to the grinding machine input buffer	automated	Handling Robot	0.5
28	Material handling	Grinding Robot moves part from the input buffer to the grinding machine working table	automated	Grinding Robot	1.5
29	Grinding (phase 2)	GRINDING trailing edge surfaces	automated	Grinding Machine	35
30	Material handling	Grinding Robot moves part from the grinding machine working table to the output buffer	automated	Grinding Robot	1.5
31	Material handling	Handling Robot moves part to the air cleaning station	automated	Handling Robot	0.5
32	Air cleaning	Air cleaning	automated	Air Cleaning Station	2
33	Material handling	Handling Robot moves part to the deburring station	automated	Handling Robot	0.5

34	Material handling	Handling Robot picks a deburring instrument from the tooling storage	automated	Handling Robot	0.5
35	Deburring	Handling Robot performs Deburring of edges on the machined surfaces	automated	Deburring Station	6
36	Material handling	Handling Robot returns the deburring instrument back to the tooling storage	automated	Handling Robot	0.5
37	Material handling	Robot moves part to the washing machine	automated	Handling Robot	0.5
38	Washing	Part Washing to remove chips and oil/emulsion film	automated	Washing Machine	3
39	Material handling	Robot moves part to the CMM machine	automated	Robot	0.5
40	Measuring	Measuring of machined surfaces in the grinding machine	automated	CMM	7
41	Material handling	Robot moves part fitted to the rotating table	automated	Robot	0.5
42	Dismounting	Dismounting of part and fixture assembly	manual	Rotating Table	1.5
43	Material handling	Labor moves the fixture (phase 2) to the storage	manual	Labor	0.6
44	Material handling	Labor moves the finished part to the output buffer	manual	Labor	0.6

Table 5.2. Sequence of operations.

A setup process carried out by the human labor (duration: 120 min) has been considered for the grinding machine when transition between first phase grinding and second phase grinding process occurs: this is the necessary time to arrange the machine and change the type of grinding wheel required for processing.

5.3 Discrete Event Simulation

5.3.1 Parts Flow

In order to represent the production cycle of the vanes, a simulation model was built on the basis of the given layout, and a number of processes were created to represent the operations carried out in the cell.

With the aim of managing the parts flow throughout the cell, products have been distinguished in terms of name for each single process: this means that a part enters a machine with a name and after the process has been carried out the product comes out with a new name. This helps identify at which stage of the production cycle a specific product is, and route it to the appropriate element in the system.

As an example, the sequence of parts, processes and products for NGV1 vane is represented in the scheme below.

Part	Process	Product
NGV1_Raw1 Fixture1	Mounting_1	NGV1_Fixt1
NGV1_Fixt1	Measuring_1	NGV1_Fixt1_measured_1
NGV1_Fixt1_measured_1	Grinding_1	NGV1_Fixt1_grinded
NGV1_Fixt1_grinded	Cleaning	NGV1_Fixt1_cleaned
NGV1_Fixt1_cleaned	Deburring	NGV1_Fixt1_deburred
NGV1_Fixt1_deburred	Washing	NGV1_Fixt1_washed
NGV1_Fixt1_washed	Measuring_2	NGV1_Fixt1_measured_2
NGV1_Fixt1_measured_2	Dismounting_1	Fixture1 NGV1_ Raw2
NGV1_ Raw2	Mounting_2	NGV1_Fixt2
NGV1_Fixt2	Measuring_3	NGV1_Fixt2_measured_1
NGV1_Fixt2_measured_1	Grinding_2	NGV1_Fixt2_grinded
NGV1_Fixt2_grinded	Cleaning	NGV1_Fixt2_cleaned
NGV1_Fixt2_cleaned	Deburring	NGV1_Fixt2_deburred
NGV1_Fixt2_deburred	Washing	NGV1_Fixt2_washed
NGV1_Fixt2_washed	Measuring_4	NGV1_Fixt2_measured_2
NGV1_Fixt2_measured_2	Dismounting_2	Fixture2 NGV1_Final

Scheme 5.1: Production cycle of NGV1: parts, processes and products.

5.3.2 Discrete Event Simulation Model

In order to analyze the system's behavior in terms of production flow, the simulation model of the system was set up with the following layout. All the elements of the manufacturing cell were modeled within the simulation software environment and specific logics and connections among elements were assigned.

Since 3D geometries can be imported in QUEST from other CAD packages, 3D files of the manufacturing cell elements were imported so to allow a better visualization of the system. The resulting layout of the discrete event simulation model is reported in Fig. 5.4.

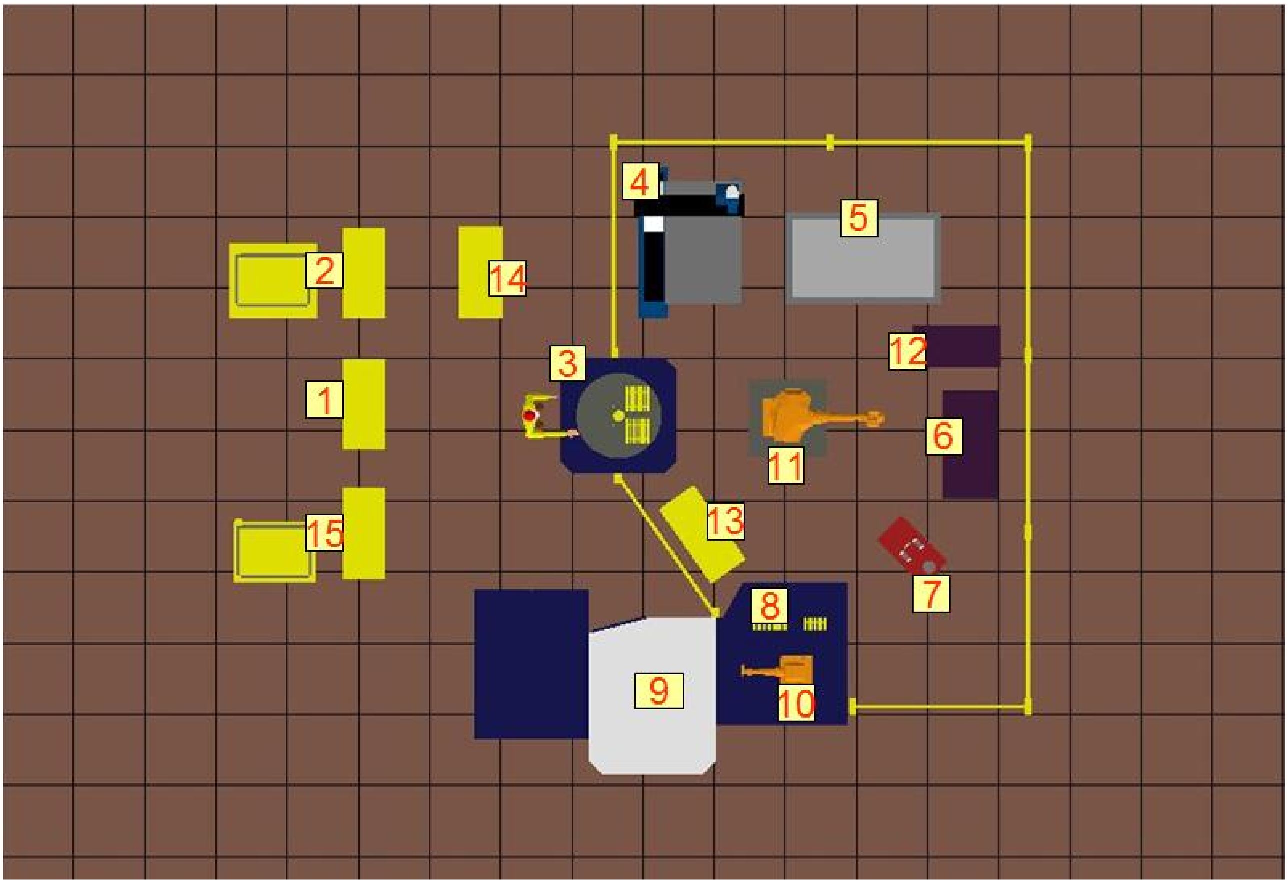


Fig. 5.4. Layout of the simulation model

N.	MANUFACTURING CELL MODEL COMPONENT
1.	Fixtures Buffer
2.	Input Vanes Buffer
3.	Vane/Fixture Assembly Rotating Table
4.	CMM – Coordinate Measuring Machine
5.	Washing Station
6.	Automatic Deburring Station
7.	Air Cleaning Station

8.	Grinding Buffer (N.2 Positions)
9.	Grinding Machine
10.	Grinding Robot
11.	Handling/Deburring Robot
12.	Tooling Storage
13.	Intermediate Buffer
14.	Buffer for vanes waiting for phase 2
15.	Output Vanes Buffer

Table 5.3. Manufacturing cell model components.

The assumptions concerning the manufacturing cell are the followings:

- All the raw materials (NGV1) are created in Source_1 and enter the cell on an input buffer
- Grinding Machine Input/Output buffers have capacity = 1 part
- The Rotating table has two buffers inside the cell (reachable by the robot), that can be employed for input and output
- Intermediate buffer can be used to store parts only while the other buffers and machines are busy
- Labor works on 3 shifts/day
- Labor works 7,5 hours per shift (6 breaks of 15 minutes per day have been introduced)
- Setup processes are only considered for grinding machines when a new phase of grinding is required
- 2 fixtures for each phase are available for NGV1 parts (total:4 fixtures)
- The vanes that are ready for second phase grinding cannot be processed until all first phase grinding processes have been completed, and they must be stored on an appropriate buffer

Parts flow in the simulation model is governed by the connection between elements: it is therefore very important to identify the correct path and corresponding connection for all buffers and machines in the system. Fig. 5.5 shows the path of NGV1 during the first phase of the production cycle.

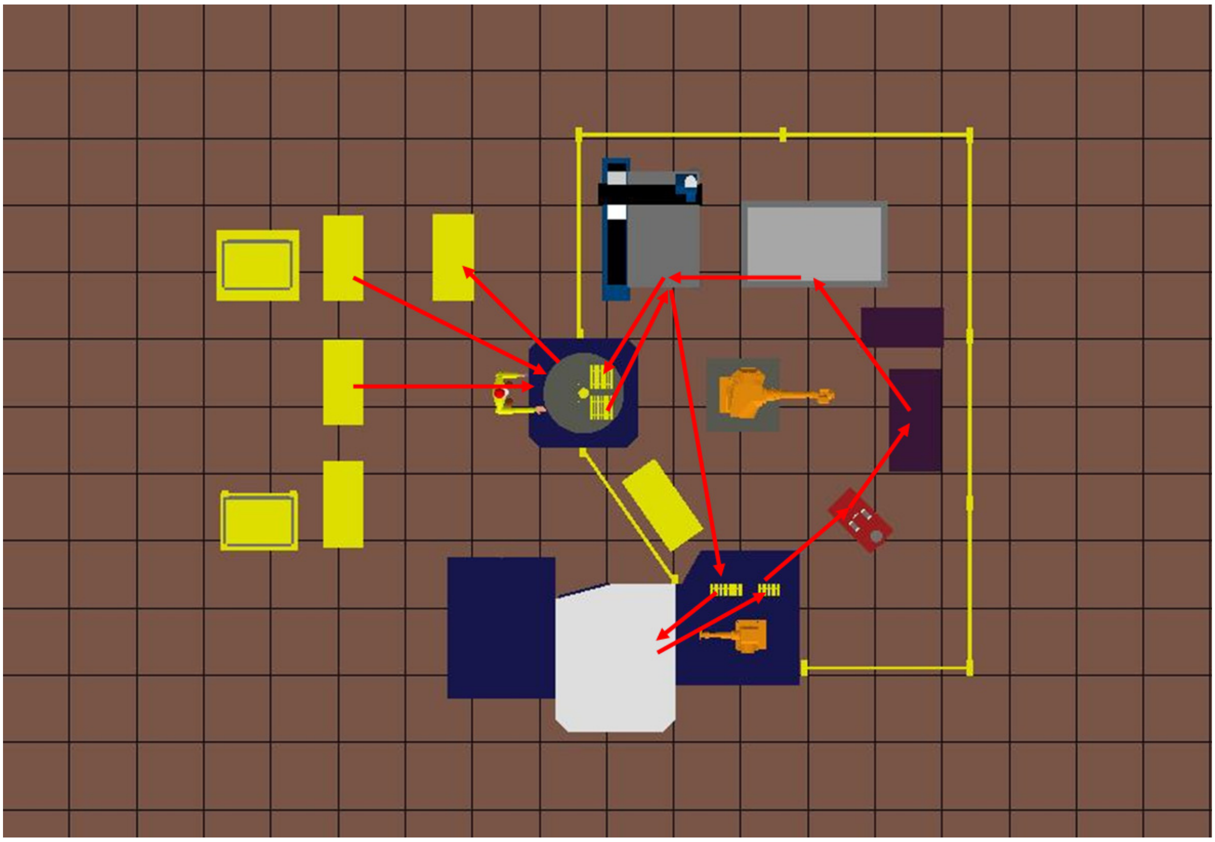


Fig. 5.5. Path of the parts during first phase.

5.4 DISCRETE EVENT SIMULATION RESULTS

Discrete Event Simulation was carried out on the previously defined model. Simulation results were generated in form of numerical report (see Excel file attached) and charts, such as pie charts and bar charts showing the utilization of the elements of the system, Fig. 5.6-5.15.

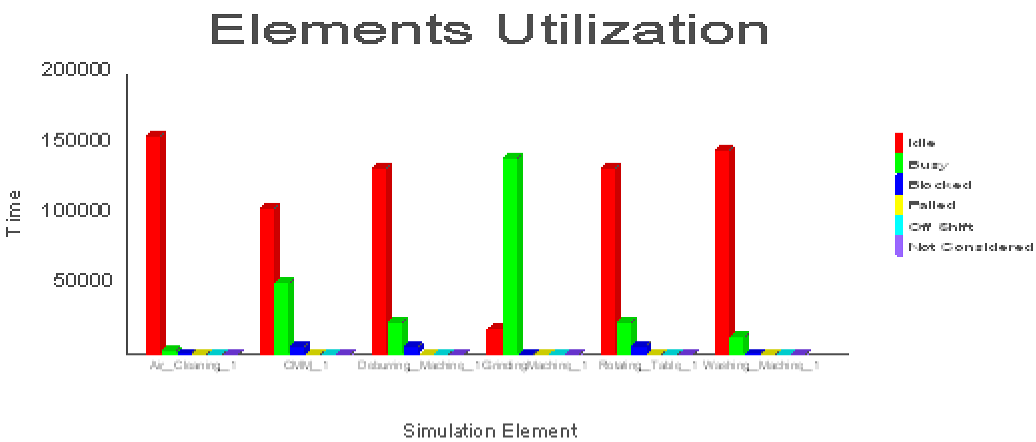


Fig. 5.6. Utilization of the elements in the cell.

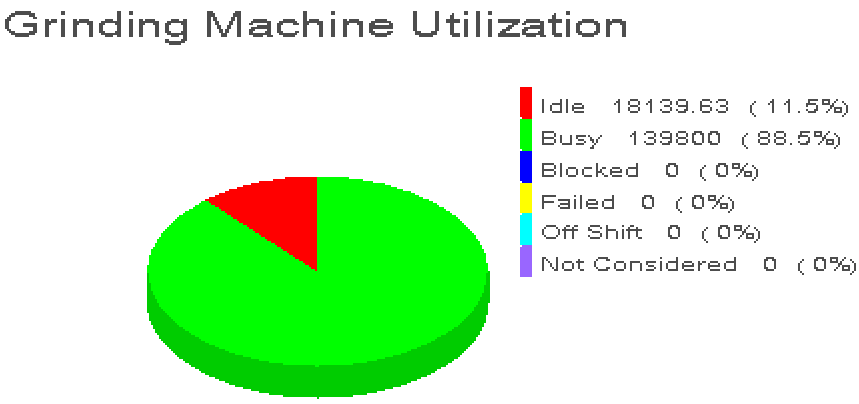


Fig. 5.7. Utilization of the Grinding Machine.

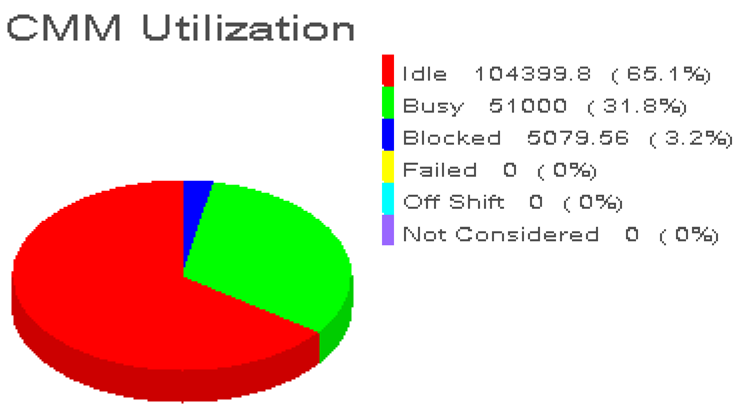


Fig. 5.8. Utilization of CMM.

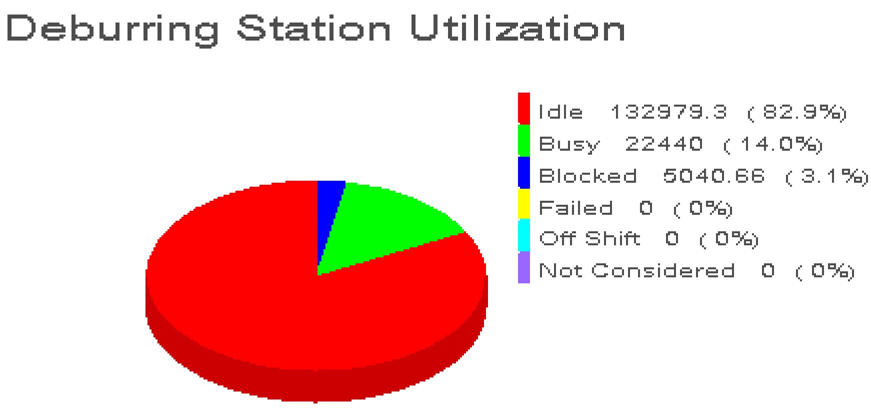


Fig. 5.9. Utilization of the Deburring Station.

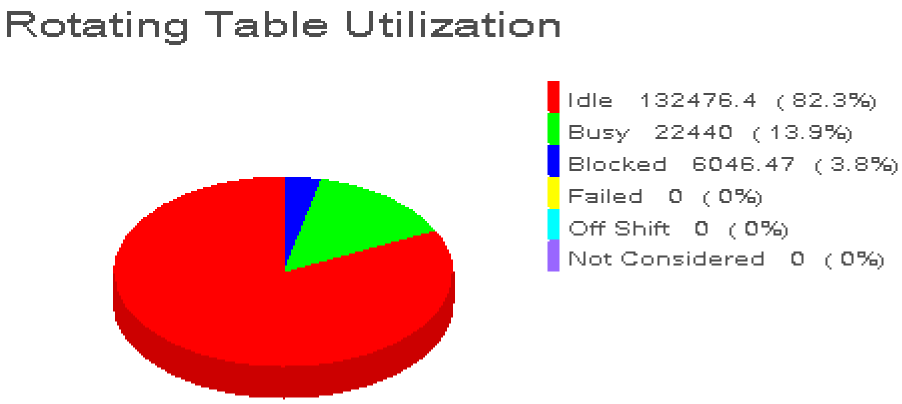


Fig. 5.10. Utilization of the Rotating Table.

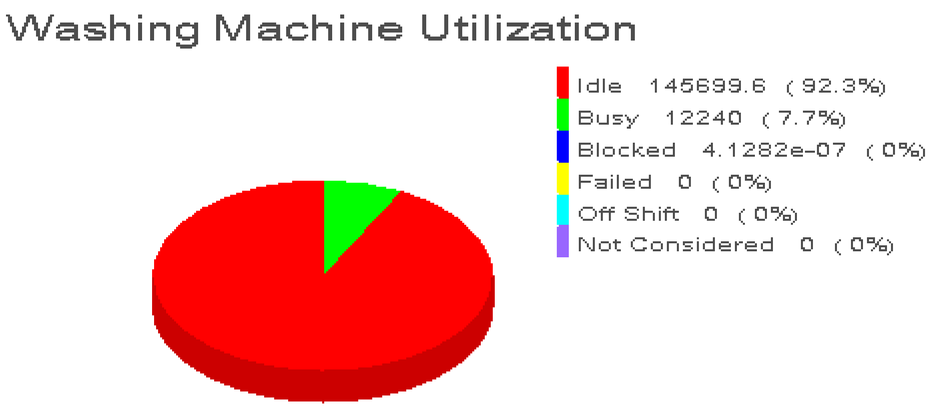


Fig. 5.11. Utilization of the Washing Machine.

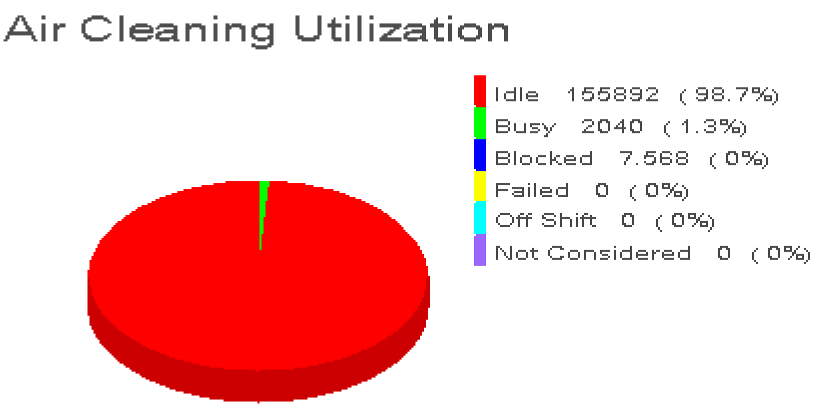


Fig. 5.12. Utilization of the Air Cleaning Station.

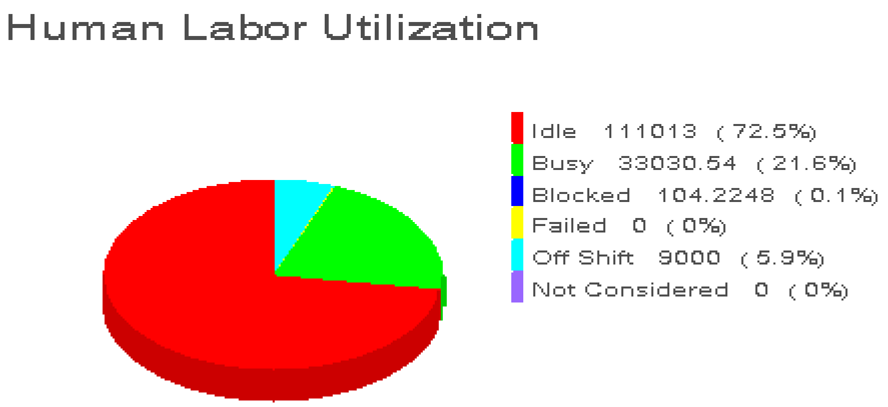


Fig. 5.13. Utilization of the Human Labor.

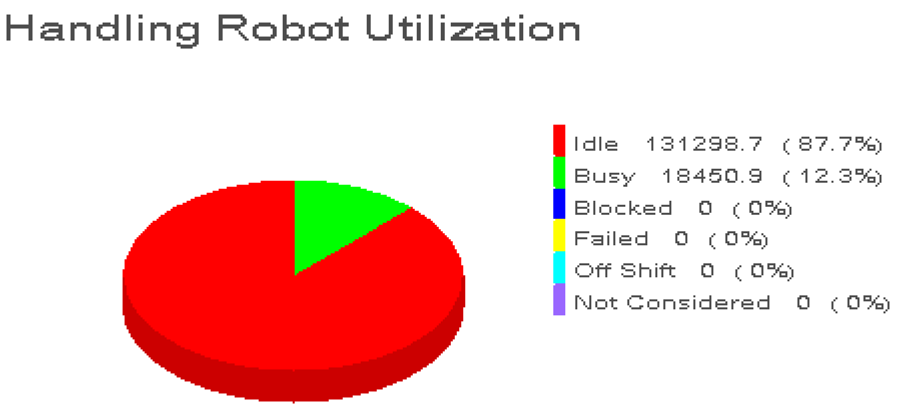


Fig. 5.14. Utilization of the Handling/Deburring Robot.

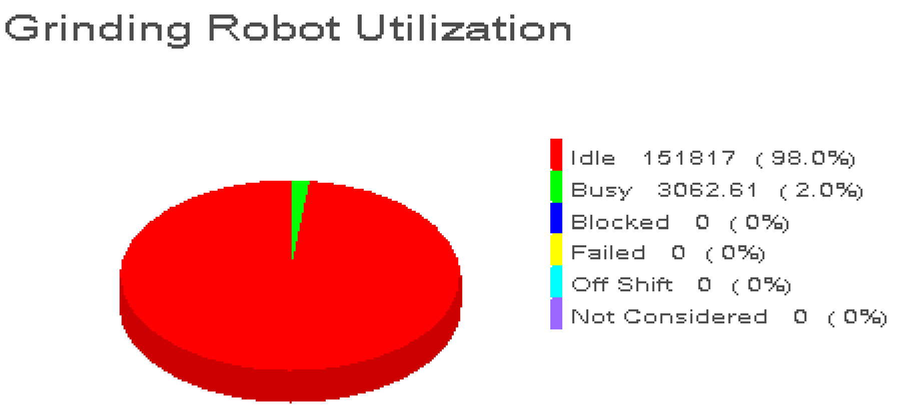


Fig. 5.15. Utilization of the Grinding Machine Robot.

From the charts above, as well as through the numerical report of the simulation, it is possible to identify the bottleneck of the system, that is the grinding machine, whose processing cycle times are very long.

It is interesting to notice that the Intermediate Buffer is never employed: this behaviour is due to the fact that only two fixtures for each phase are available in the manufacturing cell. When the grinding machine, that is the bottleneck of the system, is busy, there is still one place on the grinding machine input buffer, so it is not necessary to put the waiting part on the intermediate buffer. The subsequent other machines of the system never originate queues, since processing times are very short compared to those of the grinding machine.

The total time required to complete 34 NGV1 vanes is 43.8 hours.

Fig. 5.16 shows the number of parts inside the robotic manufacturing cell during the simulation: the maximum number of parts in the system is 2, since 2 is the number of fixtures available for each phase.

Fig. 5.16. Number of parts inside the robotic manufacturing cell.

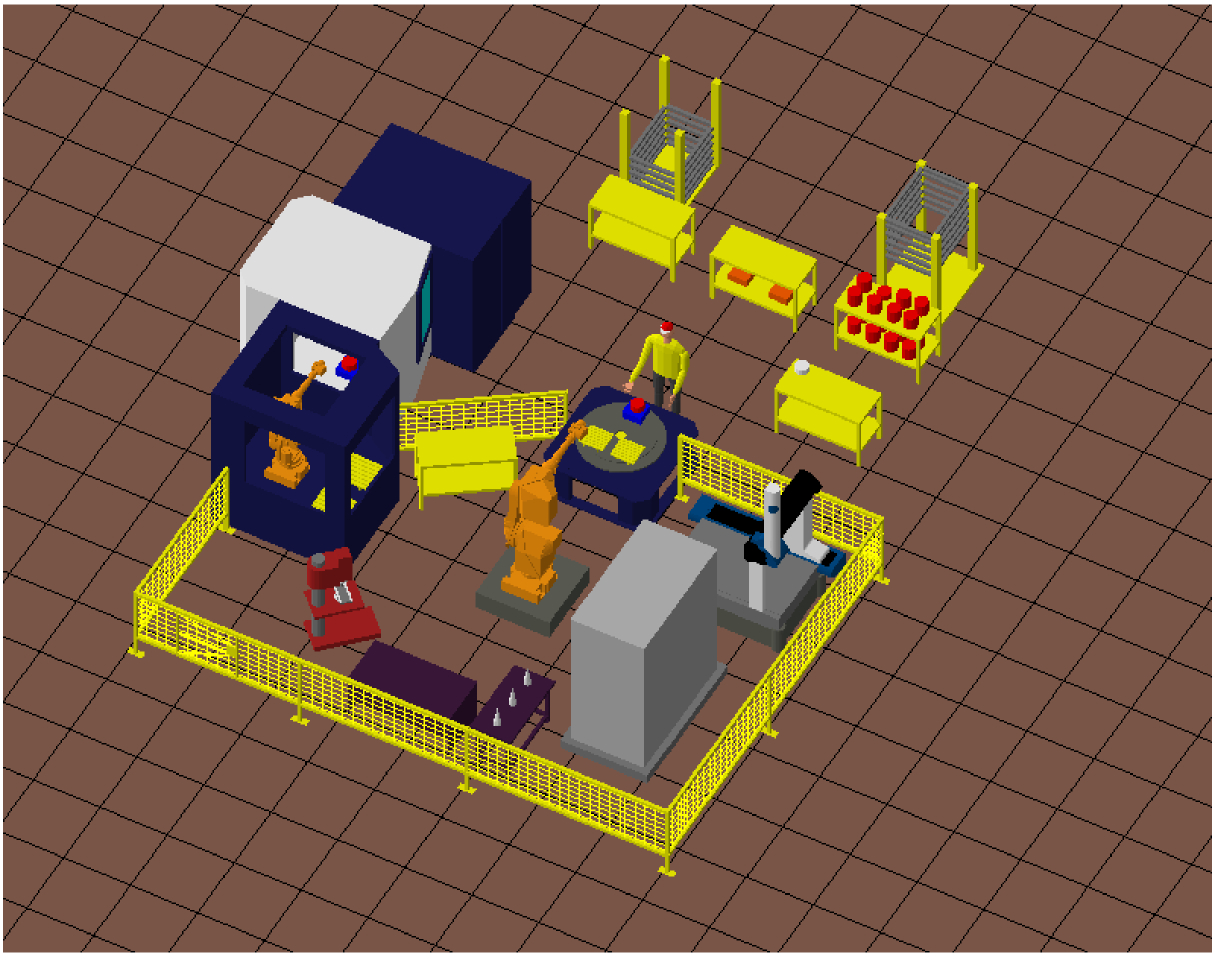


Fig. 5.17. Manufacturing cell view.

CHAPTER 6

3D SIMULATION OF MANUFACTURING SYSTEMS

6.1 INTRODUCTION

In the Digital factory, plant layout evaluation, analysis and reconfiguration should be easily carried out through the digital model associated to a manufacturing system. These problems are complex to deal with and usually they cannot be solved with the only help of DES, whose typical applications have been presented in Chapter 4 and 5. As an example, consider the case where moving devices such as AGV or robots must be introduced within a manufacturing cell: their path should be carefully planned in order to avoid collisions with machines, electrical or controlling cabinets, devices, pipes and so on. Nowadays, 3D simulation software tools can be employed to carry out this type of analysis on manufacturing systems. They allow to plan paths on a digital model without collisions, since the latter can be detected by the software and highlighted on display. 3D motion simulation can be employed to analyse interactions between equipments, operators or material handling systems, to observe whether they could collide with other objects, or even to carry out ergonomics analysis on human operators. This type of simulation tools can be employed for commissioning, supervision, diagnosis and maintenance purposes. The 3D graphical representation, integrated with the analysis of data values, data collection, statistics and collision detection, helps deal with complex systems and with their design or reconfiguration.

The aim of this chapter is to introduce the main features and applications of 3D simulation in manufacturing systems design, analysis and reconfiguration, and illustrate how one of the most utilised 3D software tools works.

6.2 APPLICATIONS OF 3D SIMULATION

3D simulation software tools can be employed to model in a 3D environment and verify a manufacturing cell layout, perform robot feasibility studies, analyse tooling and equipment, carry out a complete assessment of a manufacturing cell or an entire line. As discussed before, 3D simulation can be successfully used to carry out manufacturing systems analysis in case of presence of moving devices such as material handling systems. In modern manufacturing systems, the employment of handling or processing robots, in particular anthropomorphic ones, is becoming more and more widespread. They are able to carry out in a fast, accurate and efficient way a wide range of operations such as assembly, “pick and place”, fastening, as well as welding and painting. The use of 3D simulation software tools for planning and designing robotic manufacturing cells and plants has significantly increased in recent years:

they can be used to design robot cells and to create offline programs that contribute to reduce start-up time and to achieve a considerable degree of planning reliability. These simulation tools have been developed to meet the specific requirements of the production industry and can accomplish an amazing array of tasks. They integrate functionality for special tasks such as spot welding, laser application dispensing, and painting. With these tools, it is possible to simulate multiple robots from different manufacturers at the same time (Caputo et al., 2006).

Another typical application of 3D simulation is ergonomics analysis, that is getting more and more critical in the Digital Factory approach. Software tools are typically used for ergonomic assessment and task analysis in order to design safe working environments. This type of analysis can be used, for example, to examine manual assembly operations, in order to observe the procedure to assemble a new product, the positions of the human operator while holding and assembling the product as well as to detect the process time needed for each task.

Furthermore, the digital environment can be employed to virtually validate Programmable Logic Controller (PLC) programmes by running them on the digital models of machines, so to avoid trial and error procedures on the real manufacturing system and save time and costs.

The fields where 3D simulation applications are more widespread are certainly represented by the automotive, shipbuilding and aerospace industry. The latter in particular is characterised by huge costs related to the product development cycle and design changes. 3D simulation can contribute to define, validate, manage all the parts, processes and equipments needed to manufacture air vehicles such as aircraft or spacecraft. Integrated software tools provide for concurrent engineering and manufacturing, with all engineering phases occurring simultaneously, as required in the Digital Factory concept. In particular, the following advantages can be obtained through the employment of 3D simulation tools:

- Manufacturing plans are pre-validated in a 3D environment to avoid unexpected problems on the shop floor
- Possibility to capture and reuse manufacturing best practices
- Quality targets are met sooner due to reduction or elimination of rework
- Concurrent engineering design and manufacturing planning and process validation before committing to physical prototypes and tooling
- Creation of a common shared database, thus reducing costs and improving transparency

Therefore, 3D technology has become essential not only for design issues (as in traditional CAD systems), but also for manufacturing planning and validation based on 3D simulation.

6.3 3D Simulation Software tool: DELMIA V5

In the previous paragraph, the main applications of 3D simulation have been introduced. As all of them have different purposes, several software solutions are available on market, depending on their main focus. As an example, Jack is a human modelling and simulation tool aimed to improve the ergonomics issues, while Robcad by Tecnomatix is more oriented to the simulation of robotic cells. In this research activity, a comprehensive 3D simulation software tool called DELMIA V5 is employed to carry out simulation activities on manufacturing systems. This software offers a digital infrastructure to define, plan, create, monitor and control all processes, from early process planning and assembly simulation, robotic cell modelling and programming, ergonomics analysis, to a complete definition of the production facility and equipment. A resource data base provides a library to manage a wide range of manufacturing resource data, including machine resources, machine tools, cutting tools and gages, robots, welding guns and manufacturing process templates. This integrated infrastructure is organised in several modules, as illustrated in the following paragraph.

6.4 SOFTWARE MODULES

DELMIA V5 software is organised in five different modules: all of them are connected, but each one is related to a specific manufacturing simulation objective.

RESOURCE PLANNING MODULE

The resource planning module can be employed to model in 3D and validate a manufacturing cell setup. It provides the tools to set up and validate tooling, perform robot feasibility studies, and associate tooling and positioning equipment, including standard robots, for a complete assessment of a manufacturing cell or an entire line. It includes features for geometric modelling, kinematics modelling, and reachability studies for flexible manufacturing resources (e.g. robots). Models built with this module can be directly re-used by the Robot Simulation, Human Workplace Design and Virtual Commissioning solutions.

ROBOTICS MODULE

This module represents a comprehensive robot programming solution with advanced simulation capabilities. It provides an environment for teaching and simulating robot tasks as well as the complete manufacturing cell cycle in order to validate the mechanical processes. By validating all the robot movements and programming in the digital world, production interruptions due to manual instruction of robot task motions on plant floor equipment can be avoided. When combined with the optional arc or spot programming extensions, it provides an offline programming tool for robotic welding processes. It also cuts the time needed for new processes, as data can be re-used.

CONTROLS MODULE

Virtual control validation offers the possibility to create the mechanical, kinematical and logical behaviour of devices that can then be used to validate a PLC (Programmable Logic Controller) program in a virtual environment. By identifying PLC programming errors through simulation, the risk of damage to physical factory equipment is drastically reduced. Virtual validation before physical commissioning on the shop floor enables to significantly decrease the ramp-up time of manufacturing systems and costs for maintenance operations.

ERGONOMICS MODULE

The ergonomics module can be employed to build 3D kinematic human models, simulate various human tasks within processes and optimize the human workplace. In addition, users can perform risk factor analysis to maximize human comfort, safety, and performance through a wide range of advanced tools, analyze human postures, vision, reachability and biomechanics for compliance with ergonomic standards. This can improve worker efficiency and health-related issues.

ASSEMBLY PLANNING MODULE

This module is intended for assembly planners or simulation engineers, as it delivers assembly process tools to simulate parts and assemblies in order to validate the manufacturing process. It includes assembly process sequence, simulation, static verification of assembling processes, creation of work instruction annotations, automatic generation and instant update of work instructions following any changes. Planning and validating the manufacturing process earlier in the design stages with the ability to capture and reuse data for shop floor implementation, saves ramp-up time and avoids delays in production. This allows to avoid significant time and cost spent by companies that follow traditional manual creation and instructions process updates.

6.5 MODELLING AND SIMULATION FEATURES

For all of these modules, different workbenches are available, each offering several related workbench toolbars. Opening a specific type of document activates the corresponding workbench tools needed to edit the document, so that the application window looks somehow different depending on what type of document is under editing. The same applies to the contents of the menu bar and the commands on pulldown menus. A same document can then be analysed in a different workbench by selecting the proper option within the Start menu. Fig. 6.1 shows the appearance of the Graphical User Interface (GUI) for a process document within the Robot Task Definition workbench.

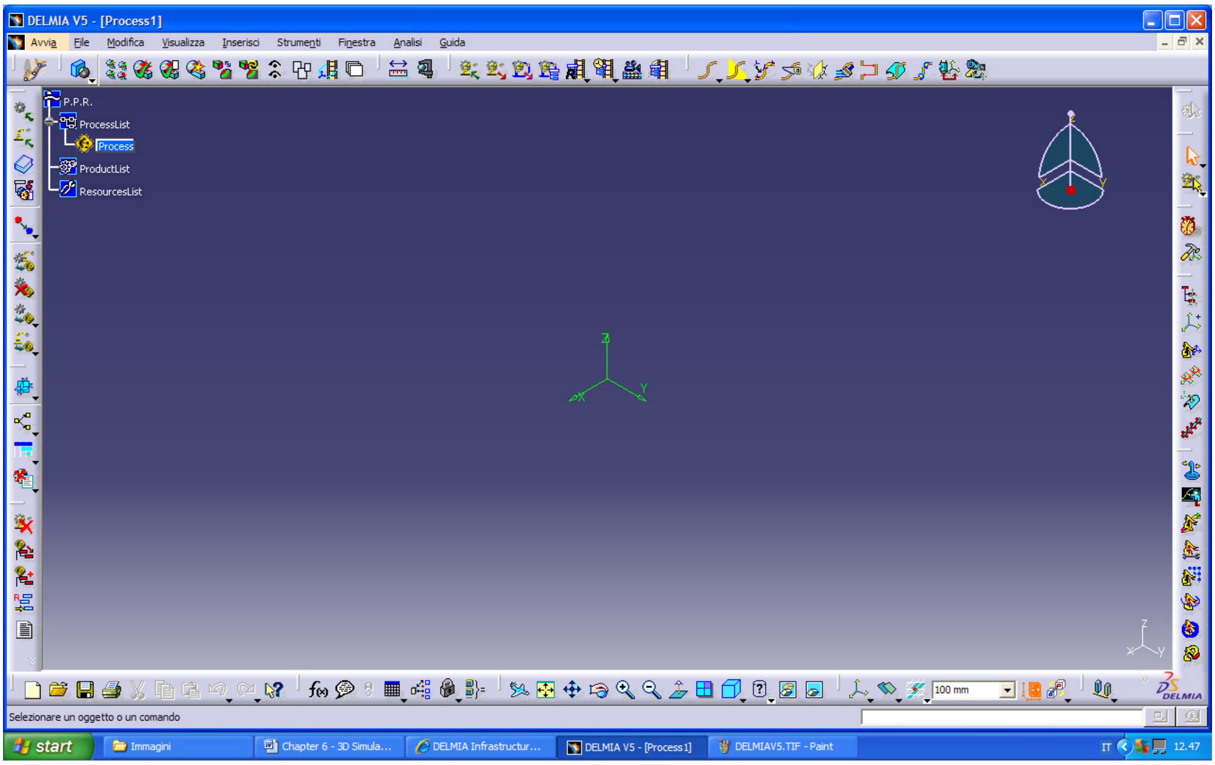


Fig. 6.1. DELMIA V5 Graphical User interface

The first step in a manufacturing system model setup is the creation of its components. In DELMIA V5, models can be built either from sketching within the part design application or from resource libraries. The part design application makes it possible to design 3D mechanical parts with a flexible user interface, and meet design requirements for parts of various complexities, from simple to advanced. Part design can be used in cooperation with other applications such as assembly design, that allows the design of assemblies with an intuitive and flexible user interface. An assembly is composed of two or more parts linked together, where the parts can be created independently in the part design application. Another important feature of this software is the possibility to create the so-called “devices”, that is to say mechanical systems provided with joints and able to perform specific motion types. The device building application offers a set of tools for modelling mechanical systems that are typically used in the manufacturing process. Such systems include robotic end-effectors (grippers, weldguns, etc.), positioning devices, presses, machines, and so on. The objective is to model forward-kinematic devices that can only be driven in joint coordinates. In this application, a mechanical system is defined in terms of rigid bodies (called parts) and articulated joints. The dialog box for the creation of a revolute joint is reported in Fig. 6.2 The parts may originate from CATIA, DELMIA, or other CAD sources. The joints characterize a combination of mechanical constraints (such as rotation about a fixed axis) and geometric constraints (such as following the surface of a part). Fig. 6.3 shows the mechanism on the PPR tree of the product, including joints, products, fixed part, and so on. Finally, the mechanical system may include closed-kinematic loops, where a collection of parts forms a closed chain. After a device has been created, the user may define a set of predefined positions (called "home positions") and a timetable to be used when moving between them, through the dialog boxes shown in Fig. 6.4-5. Tools are provided to directly manipulate the joints of a device and observe the resulting configuration.

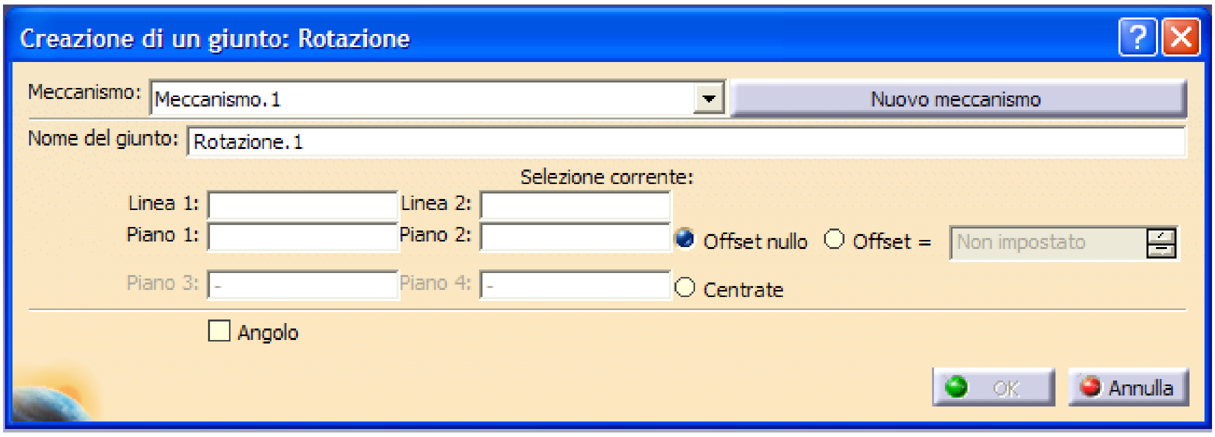


Fig. 6.2. Joint creation : Revolute joint dialog box.

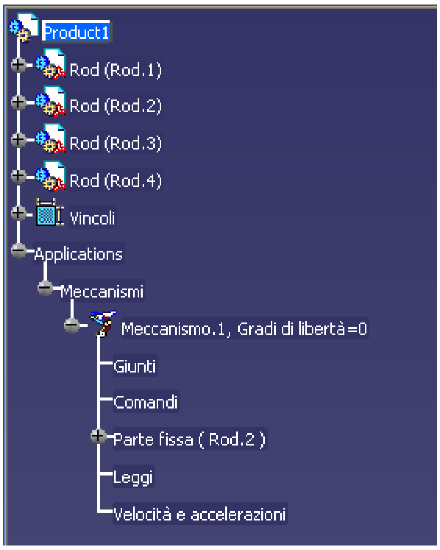


Fig. 6.3. Mechanism inserted in the product tree.

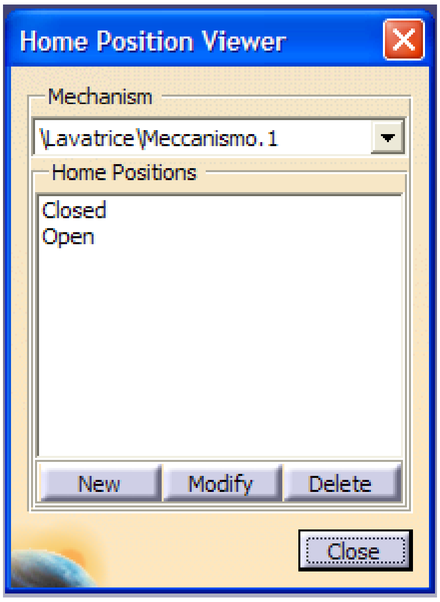


Fig. 6.4. Home positions dialog box.

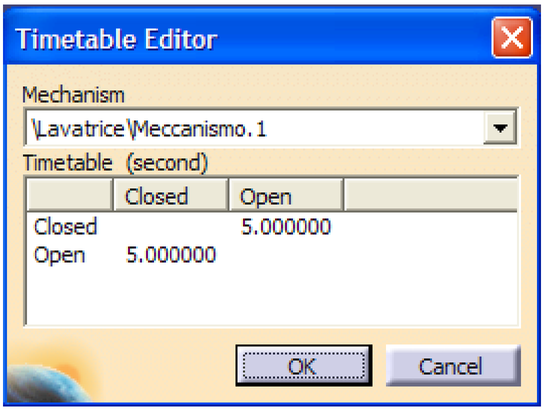


Fig. 6.5. Timetable dialog box.

The built components and devices of the manufacturing system can then be employed for simulation in different workbenches.

The Plant Layout workbench enables to create a layout design for a manufacturing plant or other type of plant. It provides an efficient, cost-effective way to lay out an initial plant design for review and validation. The initial plant design may then be expanded, evolved, and modified to continue the plant design process. The Plant Layout product can be used with other digital plant design products, such as Systems Routing, to satisfy plant design requirements. These products, together with the product portfolio, provide you with the complete ability to design and optimize your plant layout.

For the research activity presented in this thesis, one of the most important applications of DELMIA V5 concerns robot modelling and simulation. For this purpose, the Robot Task Definition workbench provides tools for 3D modelling at the manufacturing cell level. Robot models can be downloaded from a wide Standard Robot Library, containing several robot models from different manufacturers, as shown in Fig. 6.6.

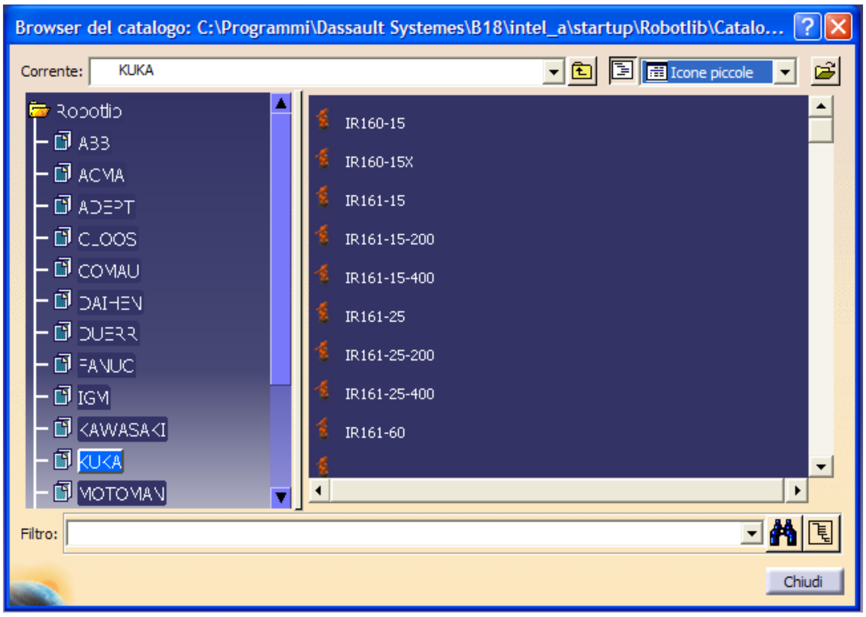


Fig. 6.6. Standard Robot Library.

The robot models included in the Standard Robot library incorporate non only the geometrical features, but also the kinematics associated to the real robot model. Joint are defined and visible, and they can be moved through the robot jogging dialog box or by direct manipulation of the robot model. Fig. 6.7 shows the robot jogging dialog box reporting all the joints with the current value and the limits for each joint. Moreover, each robot has a tool profile, accessory devices, and a motion profile defining its linear and angular speed as well as acceleration, as shown in Fig. 6.8.

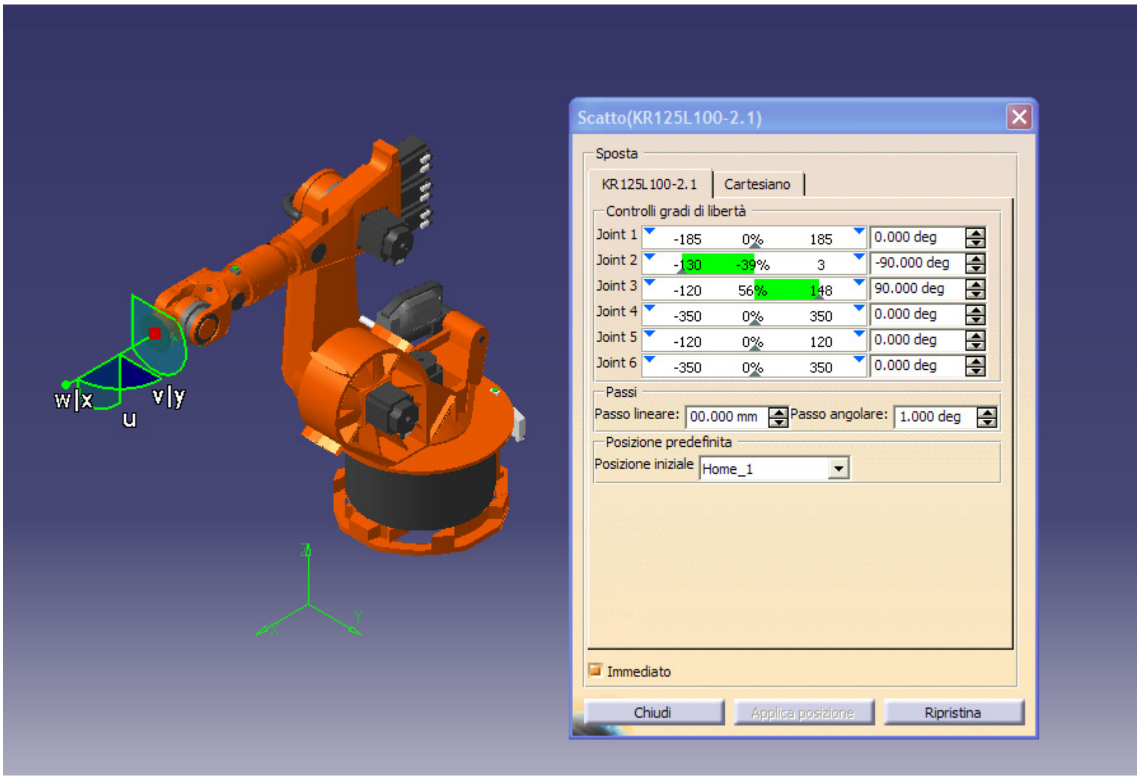


Fig. 6.7. Robot joints: robot jogging dialog box.

Fig. 6.8. Motion profile.

Moreover, it provides tools for the development of robot programs and facilities to test those programs while checking for interferences.

Within the Robot Task Definition, robot tasks and tags for robot motion can be defined are. Users can create tags and add them to tasks or can create tags in free space for clearance moves. Fig. 6.8 shows tags located on specific points of a product, in order to indicate the places that the robot should reach to perform a task.

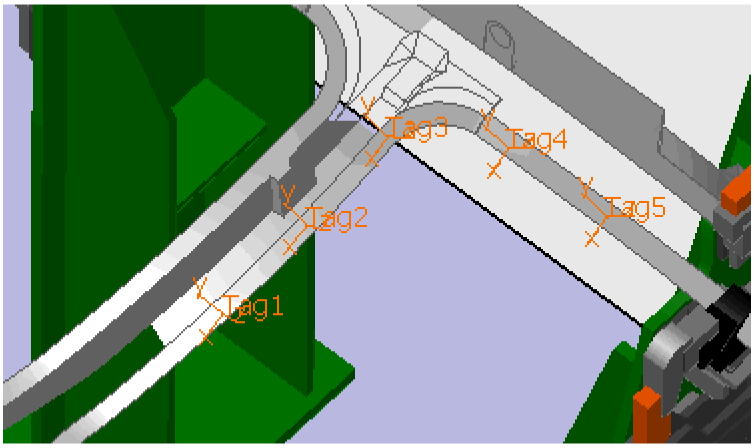


Fig. 6.9. Tags located on a product.

To develop and test robot tasks, interactive jogging and robot teaching capabilities are available, and the tasks can be simulated, one at a time. Different types of actions can be assigned to robots within their tasks: pick/drop, spot weld, and so on. Table 6.1 shows some actions that can be assigned to a robot model.

Icon	**Action**	**Consisting of:**
	Pick	Close gripper -> Pick part
	Spot weld	Close gun -> Weld time -> Open gun

	Drop	Open gripper -> Drop part
	Gun retract	Open gun
	Pick tool	Pick tool
	Drop tool	Drop tool

Table 6.1 Pre-defined robot actions.

Moreover, the workbench provides tools to perform robot feasibility studies and programming in an environment where product data and manufacturing resources can be integrated into a single 3D model. This model performs the basis for the development of robotic processes.

Once defined, the assigned tasks can be tested by performing a reachability analysis allowing to examine robot reach and access in a complex manufacturing cell, as shown in Fig. 6.9. For each activity within a task, the reachability status is highlighted.

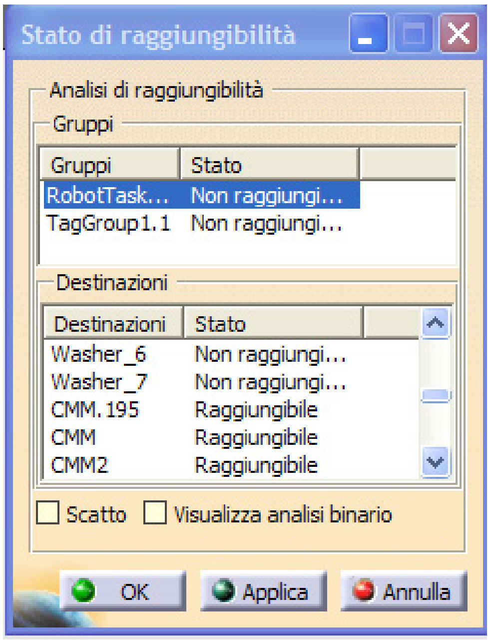


Fig. 6.10. Reachability analysis.

In addition to the basic setup commands, the workbench also contains analysis tools, for basic measuring of distances and angles or collision and band width analysis.
The output of Robot Task Definition is a manufacturing cell model that is ready for the next step: development of a complete manufacturing simulation with synchronization of all resources.

In some cases, Robotics Offline can be employed to translate V5 robot tasks into robot controller-specific programming languages. Conversely, users may load programs written in robot controller-specific languages into V5 and have their programs converted into V5 robot tasks.

Another important application in DELMIA V5 is related to ergonomics analysis. Some workbenches are dedicated to this purpose. First of all, Human Builder application specifically focuses on creating and manipulating digital humans for "first level" human-product interaction analysis. It is based on a best-in-class human modeling system and provides very accurate simulation of humans and their interactions with products to ensure they will operate naturally in a workplace tailored to their tasks. The workbench consists of a number of advanced tools for creating, manipulating and analyzing how manikins (based on the 5th, 50th and 95th percentile value) can interact with a product. The manikins can then be used to assess the suitability of a product for form, fit and function. The manikins can be intuitively created and manipulated in conjunction with the digital mock-up of manufacturing systems to check features such as reach and vision. A simple-to-use interface ensures that first-level human factors studies can be undertaken by non-human factors specialists.

Then, Human Activities Analysis specifically focuses on how a human will interact with objects in a working environment, as well as the effects of lifting, lowering, pushing, pulling and carrying on task performance. Human Activity Analysis evaluates all elements of human performance from static posture analysis to complex task activities. A range of tools and methods are available that specifically analyze how a manikin will interact with objects in the virtual environment. The NIOSH 1981/1991 and Snook and Ciriello equations measure the effects of lifting/lowering, pushing/pulling, and carrying to fully optimize task performance. A designer can determine a number of task variables such as action limit, recommended weight limit, and maximum lifting/lowering weight. Benefits include accurately predicting human performance, ensuring conformance to health and safety standards and maximizing human comfort and safety.

Finally, Human Posture Analysis focuses on how human posture can affect task performance by analyzing local and global postures, preferred angles, and comfort. It permits to quantitatively and qualitatively analyze all aspects of manikin posture. Whole body and localized postures can be examined, scored, iterated, and optimized to determine operator comfort and performance throughout the complete range of task motion in accordance with published comfort databases.

In order to create, validate, and simulate activities for human labours, Human Task Simulation can be employed. The activities that can be created for workers are:

- Walk
- MoveToPosture
- Pick
- Place
- Climb

Workers perform these activities within the PPR environment where they may walk or climb to a specific location, move from one target posture to another, and pick and place parts in the work area. These activities can be combined with DPM Assembly activities to analyze the relationship between workers and other entities within the simulation. They can be simulated and validated using the powerful process simulation capabilities from DELMIA, allowing the user to test multiple alternatives for the work humans must accomplish in a specific manufacturing environment.

After having defined the desired tasks for robots, machines and human operators, Workcell Sequencing can be used to simulate robotic manufacturing processes. It works on the workcell models developed in Robot Task Definition, Human Task Simulation, or DPM Assembly Process Simulation. In this workbench, the user can coordinate and review the performance of multiple resources working together in the same manufacturing system.

Task synchronization can be applied among all the programmable resources such as robots or human models., by using IO technology. Workcell Sequencing allows to link the resource programs to the process planning, and so creates a bridge between the resource-centric programming and the high-level manufacturing process description. Fig. 6.11 shows the Process-Product-Resource tree in the case where a process made up of two activities has been setup: in this case, activities are not under the assigned resource, but under the process.

Fig. 6.11. Process and activities in Workcell Sequencing.

Workcell Sequencing can be used to see simulations of robotic movement within a manufacturing cell, since the simulation reproduces both simple and complex robotic manufacturing processes exactly as they are defined.

Moreover, Gantt charts as well as PERT charts for each process can be generated in order to analyse the process from a logical and time-related point of view.

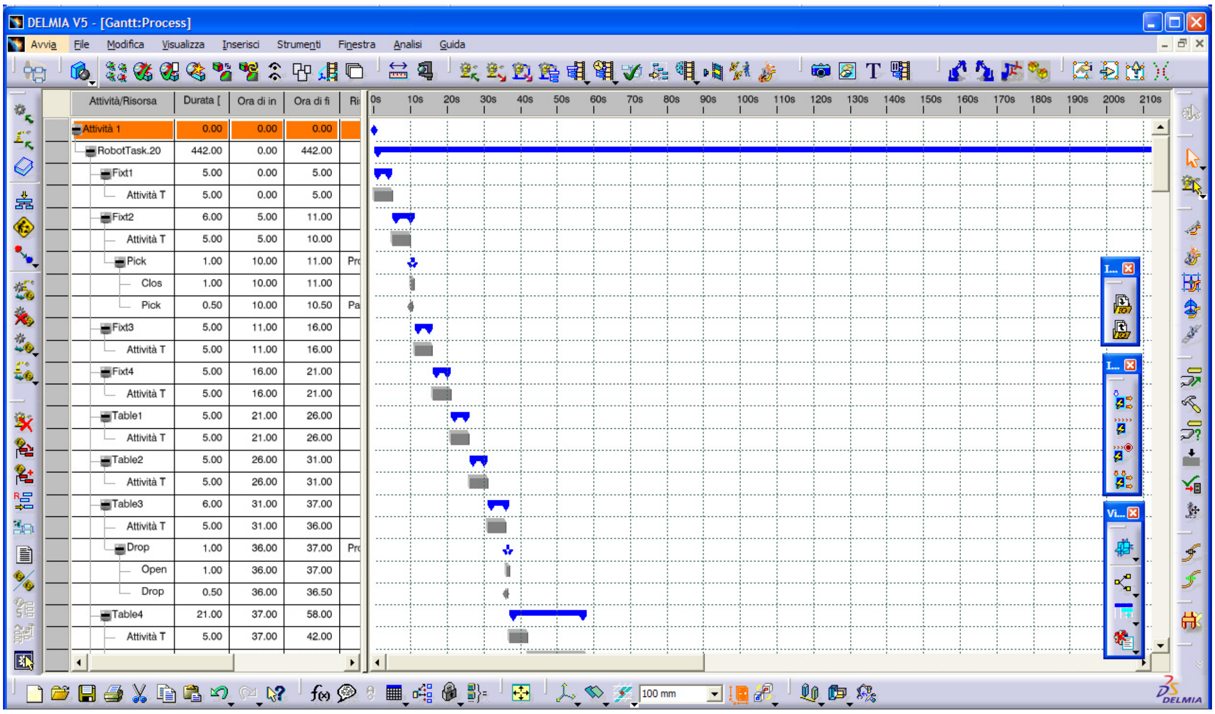


Fig. 6.12. Example of a process Gantt chart.

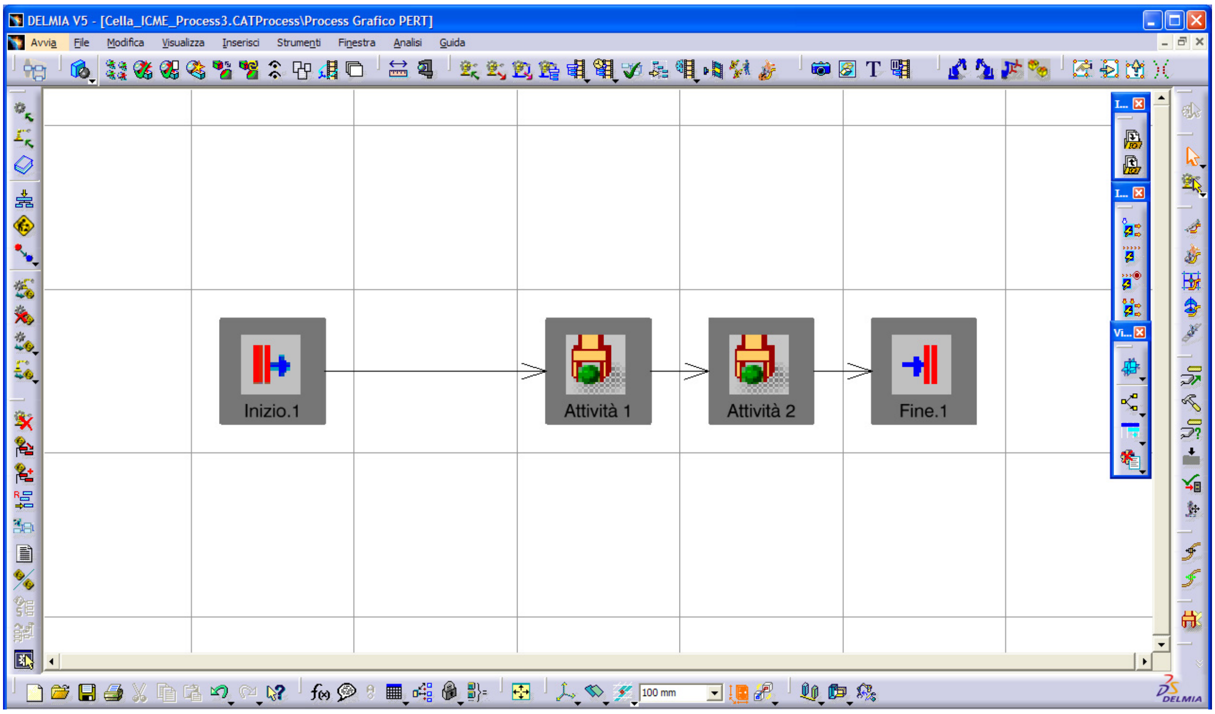


Fig. 6.13. Example of a process PERT chart.

CHAPTER 7

SIMULATION AND RECONFIGURATION OF A MANUFACTURING CELL FOR DIGITAL FACTORY CONCEPT IMPLEMENTATION

7.1 INTRODUCTION

The Digital Factory concept has been introduced in the field of production engineering as a new approach to improve product quality and production system performance through integration of diverse digital methodologies and tools. As discussed in the previous chapters, the focus and key factor in this paradigm is the combination of the various planning and simulation processes by using common data for all applications. This approach would enable collaboration with the employment of virtual models for different purposes and different levels of detail (Kühn, 2006).

The role of simulation is fundamental in this approach, and can have several uses on the basis of the category of the simulation software tool employed. Modelling and simulation of a digital mock-up of a manufacturing system can be employed to analyse the system's production performance, through Discrete Event Simulation (DES), or can be adopted to analyse layout, ergonomics and robotics issues, through 3D motion simulation.

Models are intended to support management decisions about the system and a single model will often not be capable of supporting all decisions. Rather, different decisions require different models because various aspects of the design and operation of the system will be important for the questions being asked of the model (Fowler et al., 2004).

In this chapter, an existing manufacturing cell dedicated to the production of aircraft engine components in a real industrial plant is modelled and simulated through DES with the aim to examine the system's performance in terms of productivity, utilization of the available facilities, bottlenecks of the system, etc. In order to evaluate the aspects concerning the balancing of facilities utilization and productivity enhancement, production flow and attributes of the available facilities in the cell need to be studied in terms of labor task allocation, buffer capacity, number of utilized fixtures, distribution of work load.

The paper discusses how simulation is used to support the design and enhancement of performance of the Manufacturing Cell, and it addresses the problem of designing and setting the right equipment as well as the layout of the system. The visual and numerical analysis of the simulation is used as a basis to suggest possible areas of improvement that could increase efficiency and productivity of the cell, and a new simulation model is built in order to evaluate the effects of the proposed modifications on the cell.

Afterwards, a 3D simulation software is employed to study the manufacturing cell with regard to the configuration of a suitable layout as well as to the aspects related to robot motion, as the possibility to reach all the objectives and the safety of movements throughout the manufacturing cell. The results of this simulation, including the layout modifications and the estimated robot loading/unloading and displacement times are then employed to input detailed data in a Discrete Event Simulation (DES) software, where the behaviour of the manufacturing cell can be analysed with reference to productivity and utilization of the available resources.

7.2 THE MANUFACTURING CELL

The manufacturing cell under study is a real cell located at the facilities of the aircraft engine manufacturing company Avio Spa, Pomigliano d'Arco, Naples. In this huge factory plant, called Turbine Airfoil Center, main activities are related to design and manufacturing of blades and vanes for jet engines. The layout of the Turbine Airfoil Center Plant is shown in Fig. 7.1.

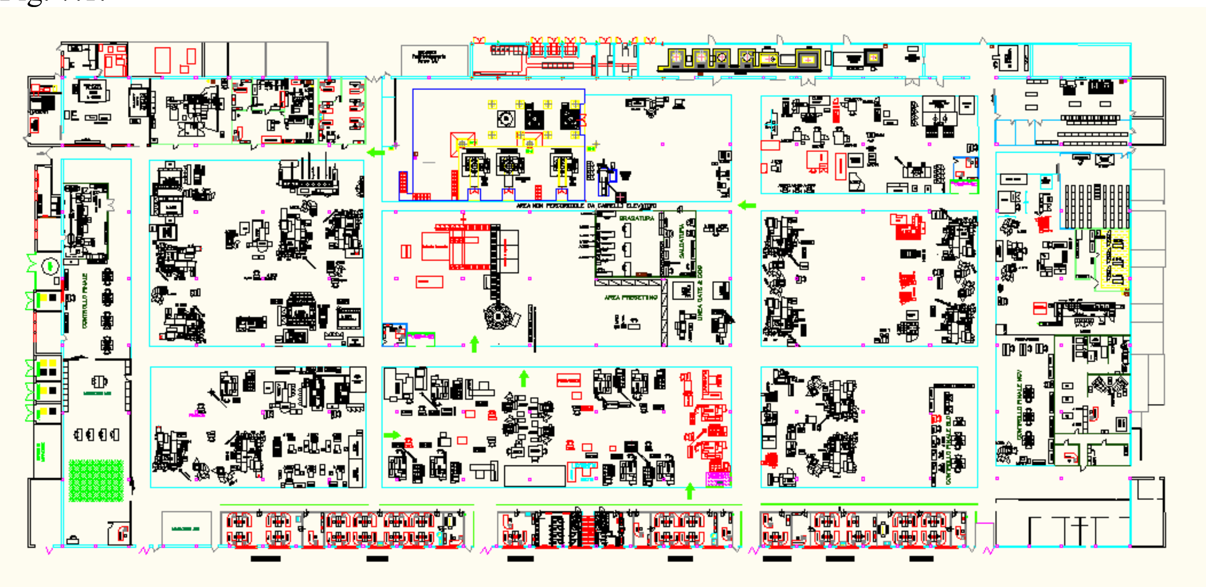


Fig. 7.1. Turbine Airfoil Center Plant.

Fig. 7.2 illustrates some examples of products fabricated within the aircraft engine manufacturing company, including turbine vanes and blades as well as fairings.

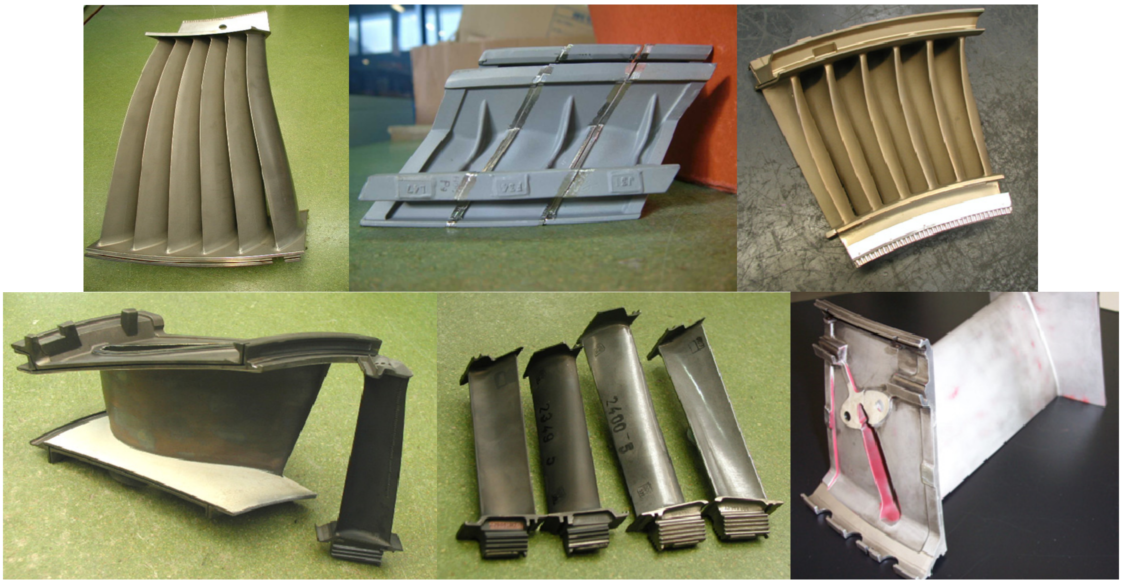


Fig. 7.2. Examples of vanes, blades and fairings produced in the factory plant.

The typical production cycle for vanes involves a number of subsequent operations, including mechanical processes and special processes, such as coating, grinding, benching, brazing, ageing, cleaning, EDM, FPI, plasma spray, dimensional and visual inspection, welding, electro chemical capillary drilling. Fig. 7.3 shows vanes current process flow.

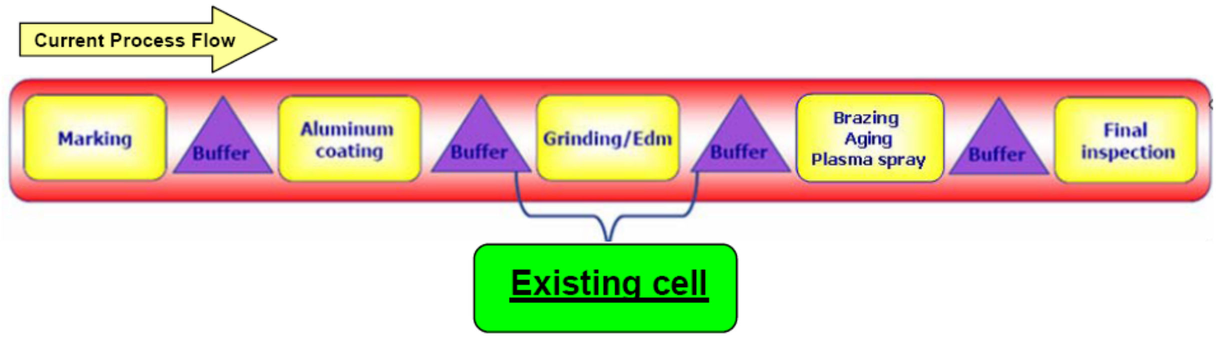


Fig. 7.3. Vanes current process flow.

In particular, the manufacturing cell under study is dedicated to the execution of two-phase grinding operations on 3 stages of turbine vanes (called NGV1, NGV2 and NGV3) which all together compose a kit. For each type of product, the number of parts required to complete a full kit is reported in Table 7.1.

Sequence	Product	Kit Quantity
1.	Part A	21
2.	Part B	22
3.	Part C	24

Table 7.1. Sequence, name and quantity of vanes for a full kit.

The three kinds of parts enter the cell one by one in a certain sequence and in a definite batch size. According to company perspective and target, the total production time during processing in the manufacturing cell is relatively high, with consequent delay of the cell in fulfilling the demand generated by the other cells in the plant. This delay time propagates in every connected cell, making the manufacturing cell under study the bottleneck of the total system. Thus, lead time reduction in the manufacturing cell is crucial to enhance the total productivity of the plant. In order to analyze the possible areas to improve the manufacturing cell efficiency, the cell was analyzed in details to build a digital model suitable for DES.

The layout of the manufacturing cell is represented in Figure 7.3, where all the components (machines, buffers, and operators) are numbered according to Table 7.2.

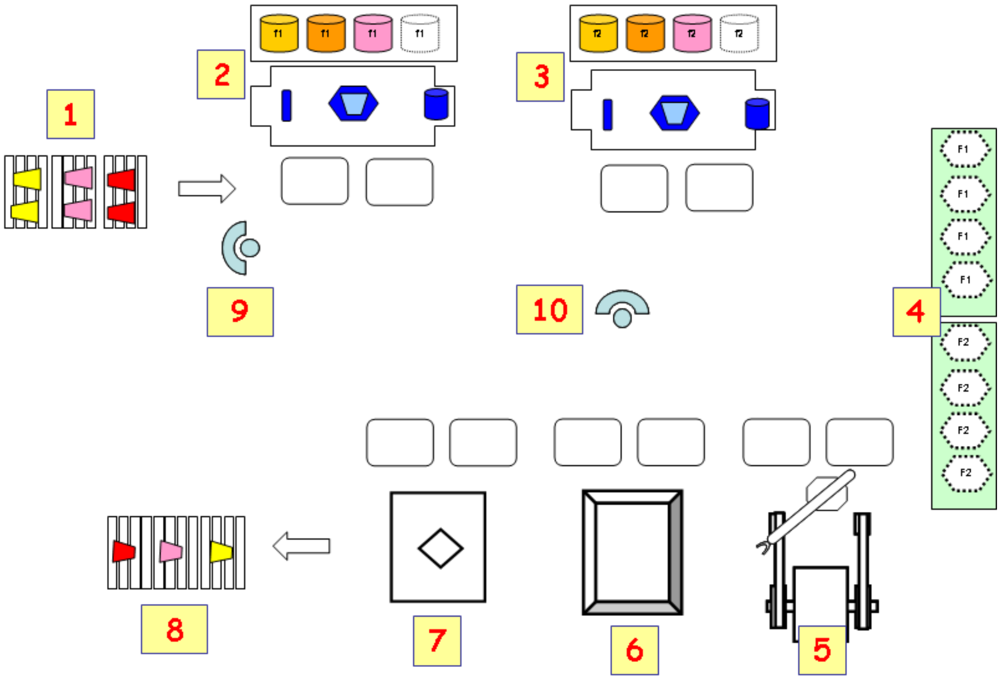


Fig. 7.4. Layout of the existing Manufacturing Cell

N.	Name of Component
1.	Input Storage
2.	Grinding Machine #1
3.	Grinding Machine #2
4.	Intermediate Storage
5.	Deburring Station
6.	Washing Machine
7.	Coordinate Measuring Machine (CMM)
8.	Output Storage
9.	Labor 1
10.	Labor 2

Table 7.2: Components of the manufacturing cell.

The production cell consists of four classes of machines: two grinding machines, a coordinate measuring machine (CMM), a washing machine and a deburring station. Moreover, there are different types of storage buffers: those with small capacity are used as input/output for machines, two intermediate buffers are placed at one side of the cell to collect the parts that cannot be accumulated out of the machines, and an input buffer and an output buffer are employed for raw and finished parts respectively.

The production cycle of the 3 parts requires 2 phases of grinding operations (to grind feature 1 and feature 2) as well as a number of subsequent operations used to finish and verify the quality of the products: to do this, they need to be moved throughout the cell by the labors. The production cycle of the 3 parts is identical, but involves slightly different cycle times. The sequence of all the operations that compose the entire process can be summarized as follows.

The raw parts arrive at the input storage and are checked and identified by Labor 1. Then, they are moved to Grinding Machine 1, where they are mounted by Labor 1 on the corresponding fixture 1 (different according to the part type), machined to create feature 1, and dismounted from the fixture. After this, the parts are moved by Labor 2 to the CMM, where they are dimensionally verified. The product of the first phase is then ready to be processed for the second phase on Grinding Machine 2. On this machine, parts are mounted on the corresponding fixture 2 (different from that of phase 1), machined and finally dismounted from the fixture. The parts are then brought by Labor 2 to the deburring machine where undesired material such as burrs is removed, and to the washing machine to eliminate powders and sticking burrs. Finally, they are measured on the CMM to carry out dimensional verifications before exiting the cell.

In Table 7.3, all the described operations are reported in sequence, with indication of the element on which they are performed.

Process	**Operations**	**Component**
Document check	Vane preparation	Input Storage
Parts identification	Reading of part and serial number	Input Storage
Mounting	Loading of part into fixture 1	Grinding Machine #1
Fitting up	Loading of part and fixture on the pallet	Grinding Machine #1
Grinding (phase 1)	Grinding feature 1	Grinding Machine #1
Dismounting	Disassembly of the part	Grinding Machine #1
Measurement	Measuring of machined surfaces	CMM
Mounting	Disassembly of the part	Grinding Machine #2
Fitting up	Loading of part into fixture 2	Grinding Machine #2
Grinding (phase 2)	Grinding feature 2	Grinding Machine #2
Dismounting	Disassembly	Grinding Machine #2
Deburring	Deburring of edges	Deburring Machine
Washing	Washing of part to remove chips and oil	Washing Machine
Measurement	Measuring of machined surfaces	CMM

Table 7.3: Sequence of operations carried out in the cell.

For each of these processes, the specific cycle times for each vane type (NGV2, NGV4, NGV7) have been identified. A setup process carried out by the human labor (duration: 120 min) has been considered for both the grinding machines when transition between grinding process of two different types of vanes occurs: this is the time required to arrange the machine, change the fixture type and change the grinding wheel necessary for processing.

7.3 DISCRETE EVENT SIMULATION OF THE MANUFACTURING CELL

In the perspective of an explorative study of the existent manufacturing cell aimed to find possible improvements, modelling and simulation of a virtual model of the cell was performed using DELMIA QUEST software.

In order to simulate the production cycle of a full kit of products, a model was built on the basis of the given layout, and a number of processes were created to represent all the operations carried out in the cell.

In the perspective of Discrete Event Simulation, the following data are fundamental in order to set up a valid and credible model of the manufacturing system:

- Sequence of operations
- Cycle times
- Set-up times
- Part routing criteria
- Working hours per day
- Shifts
- Buffers capacity
- Distance among machines

On the other hand, detailed geometries and kinematics of the elements composing the manufacturing system, such as machines, buffers, etc. are not relevant in terms of impact on simulation results. The 3D visual representation is helpful to visualize and easily understand how the manufacturing system works, but does not affect the behavior of the system, that is defined by its logic.

7.3.1 PARTS FLOW

In order to represent the production cycle of the vanes, a model has been built on the basis of the given layout, and a number of processes have been created to represent the operations carried out in the cell.

To manage the parts flow throughout the cell, products names have been distinguished for each single process: this means that a part enters a machine with a name and, after each process, the product comes out with another name. This helps identify at which stage of the production cycle a specific product is, and route it to the appropriate element in the system.

As an example, the sequence of processes and intermediate products for vane NGV2 is represented in Table 7.4, where parts, processes, and products are represented in the first, second and third column respectively.

Part	Process	Product
NGV2_Raw1 Fixture1	Mounting_1	NGV2_Fixt1
NGV2_Fixt1	Grinding_1	NGV2_Fixt1_grinded
NGV2_Fixt1_grinded	Dismounting_1	Fixture1 NGV2_grinded1
NGV2_grinded1	Measuring_1	NGV2_Fixt1_ Raw2
NGV2_Fixt1_Raw2 Fixture2	Mounting_2	NGV2_Fixt2
NGV2_Fixt2	Grinding_2	NGV2_Fixt2_grinded
NGV2_grinded2	Dismounting_2	Fixture2 NGV2_grinded2
NGV2_Fixt2_grinded	Cleaning	NGV2_Fixt2_cleaned
NGV2_Fixt2_cleaned	Deburring	NGV2_Fixt2_deburred
NGV2_Fixt2_deburred	Washing	NGV2_Fixt2_washed
NGV2_Fixt2_washed	Measuring_2	NGV2_Final

Table 7.4: Production cycle of NGV2.

The same processes will be carried out also on NGV4/7 vanes, in the same sequence but with different cycle times.

7.3.2 DES Model

In order to analyze the system's behavior in terms of production flow, the simulation model of the system was set up with the layout in Fig. 7.4. As illustrated in Chapter 4, the DES logical model is made up of two types of logical components: parts and elements. The products of the manufacturing cell were modelled as parts, as they are entities that flow through the model, moved from element to element and processed, without an internal logic. On the other hand, all the components of the manufacturing cell, including machines, buffers and labors, were modeled as elements, each one having its own logics. Further elements were introduced in the model: a source, by which parts are created and released in the model, and a sink, where final products are destroyed.

Then, connections between elements were created in the virtual model: they have strong influence in determining the behavior of the system as they represent the logical links between elements, providing the mechanism for parts to move from one element to another.

Finally, processes (including cycle processes, setup processes, load / unload processes) were created by indicating time and resources needed for all the operations in the cell, and they were associated to the corresponding elements, to define what happens to each type of part as it moves through that element.

The resulting virtual model of the described manufacturing cell is represented in Figure 7.5, where numbers identify all the components of the cell.

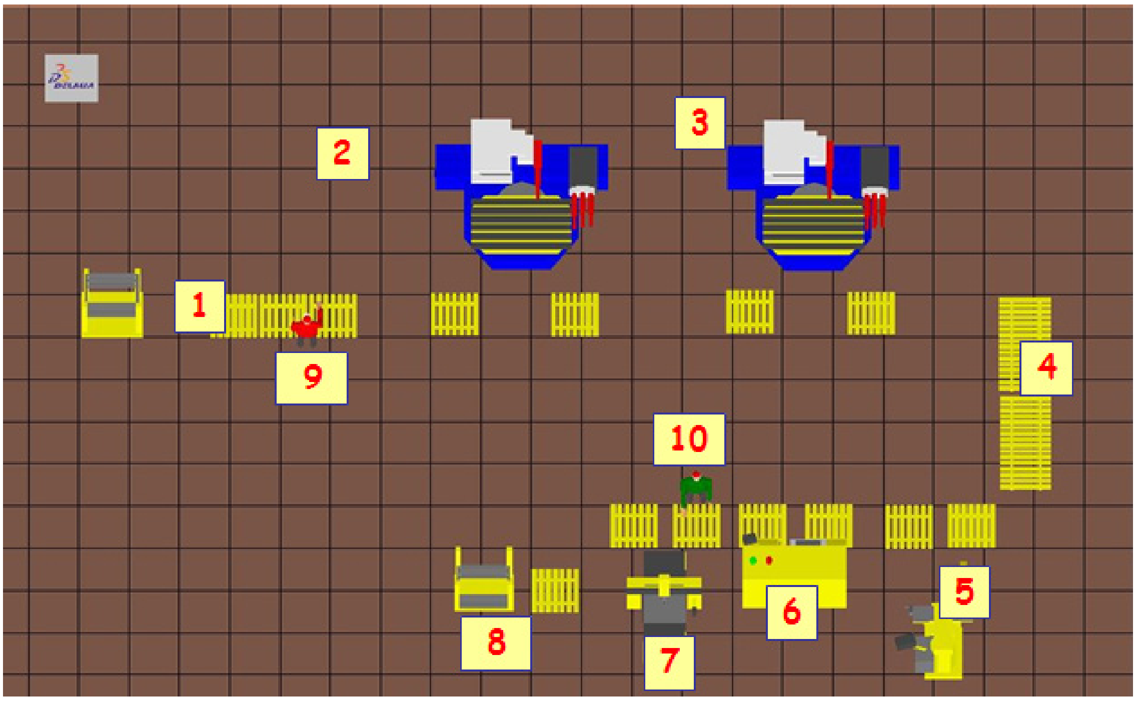


Fig. 7.5. Discrete Event Simulation Model.

The first simulation case is characterized by the assumption that the first grinding operation (Grinding Phase 1) can be only executed on Grinding Machine 1 (Blohm1), while the second grinding operation (Grinding Phase 2) can be only executed on Grinding Machine 2 (Blohm2).

The other assumptions, common to the three simulation cases, are the followings:

- All the raw materials (NGV1/2/3/4/5/6/7) are created in **Source_1** and enter the cell on a buffer
- Machine Input/Output buffers have capacity = 1 part for all the machines except for the Mounting table, that has a higher capacity (= 3 for the output buffer)
- Intermediate buffers are used to store parts only while the other buffers are full (for example, if a part is ready to enter the Blohm1 for Grinding Phase 1, but the Blohm1 is working and there is already one part waiting in the input buffer of the machine)
- Fixtures and parts mounted on fixtures can be only transported by the robot, whose motion speed has been set to approximately 12-13 m/min
- The labor can only handle parts without fixtures
- Labor works 7,5 hours per shift (6 breaks of 15 minutes per day have been introduced)

- Setup processes are only considered for grinding machines when a new type of vane requires processing (for example, if the last processed part was of type NGV1 and the next is NGV2).
- Before starting the second phase grinding, all the first phase grinding have to be completed on that type of vane

Parts flow in the simulation model is governed by the connection between elements: it is therefore very important to identify the correct path and corresponding connection for all buffers and machines in the system. Fig. 7.6-7 show the path of a vane during the first phase and second phase of the production cycle respectively.

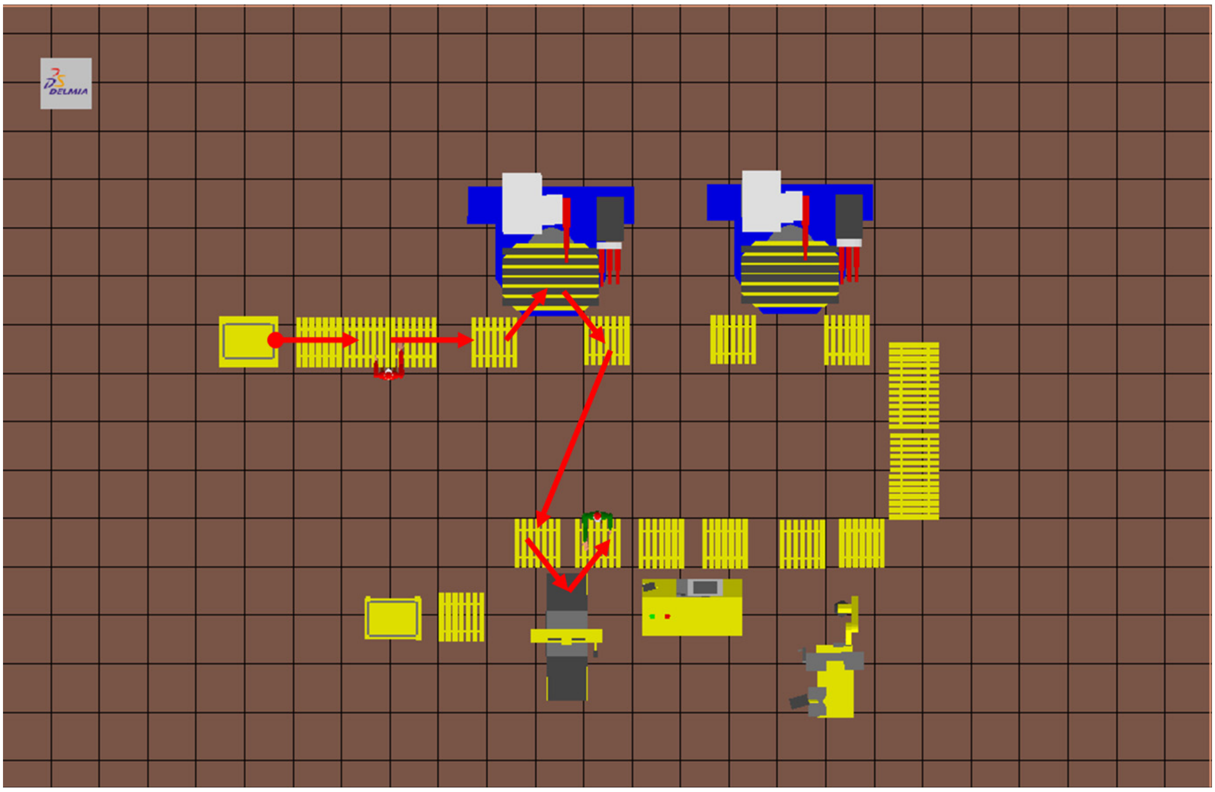


Fig. 7.6. Parts flow during first phase.

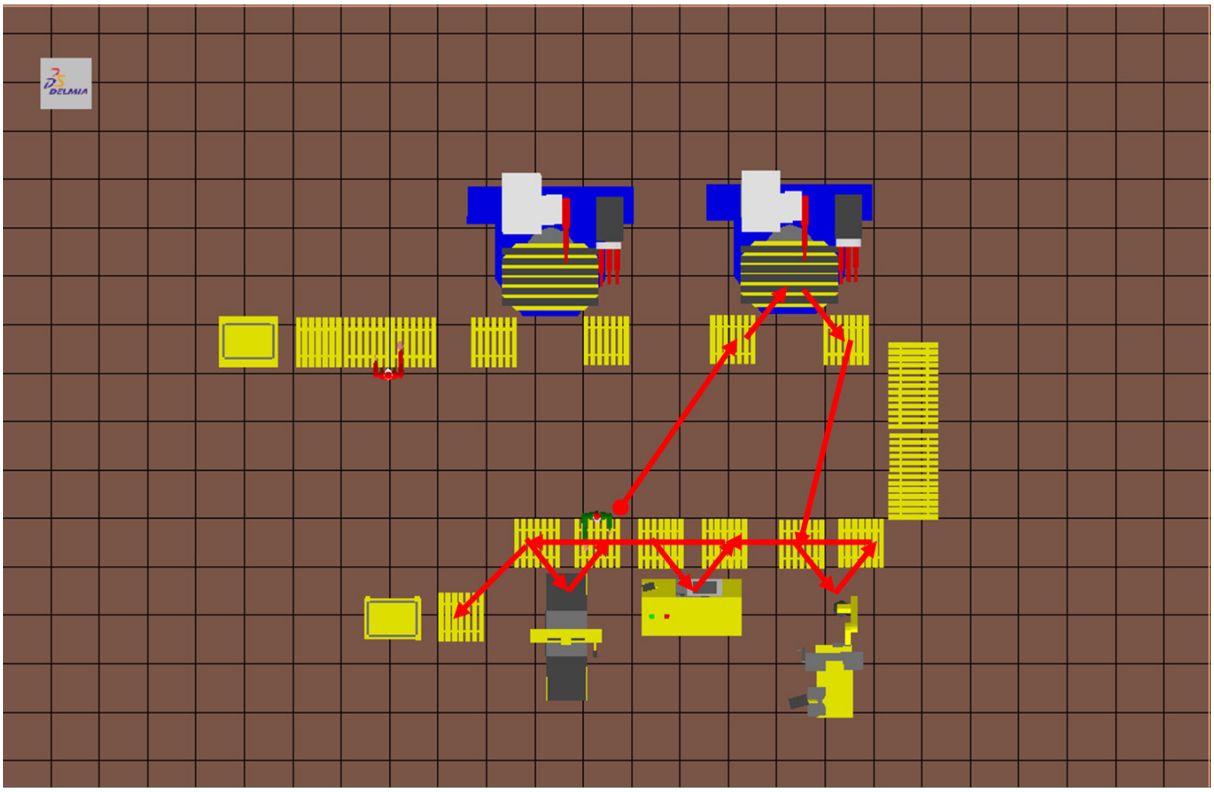


Fig. 7.7. Parts flow during second phase.

7.3.3 DES Results

Discrete Event Simulation was carried out on the previously defined model. Simulation results were generated in form of numerical report and charts, such as pie charts and bar charts showing the utilization of the elements of the system.

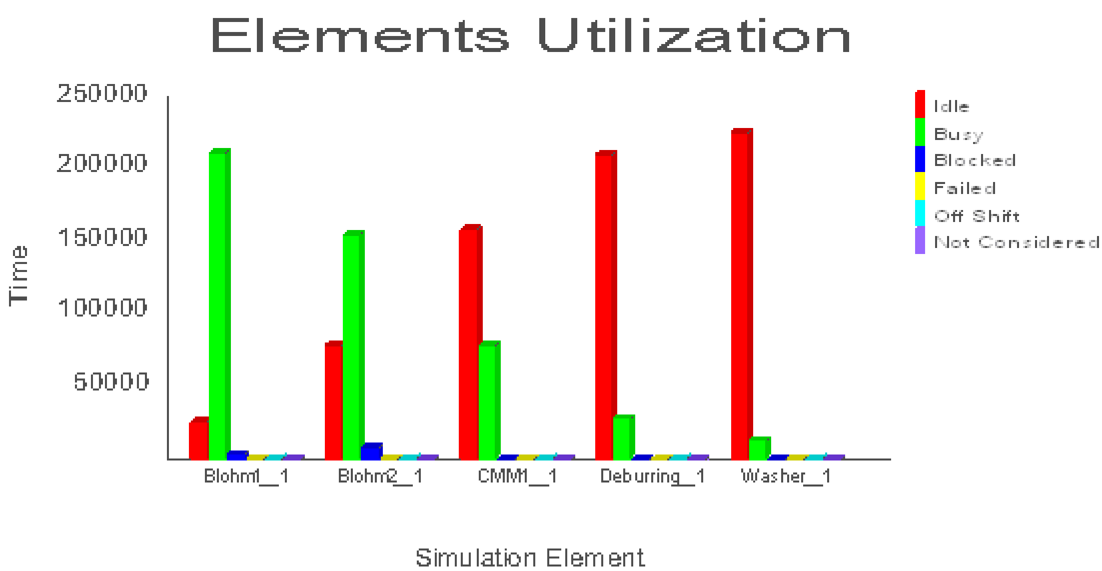


Fig. 7.8. Utilization of all the manufacturing cell machines.

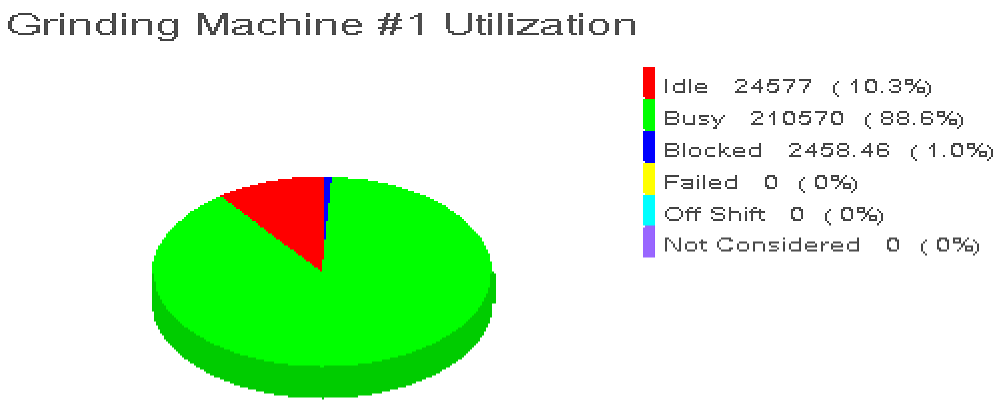


Fig. 7.9. Grinding Machine #1 Utilization.

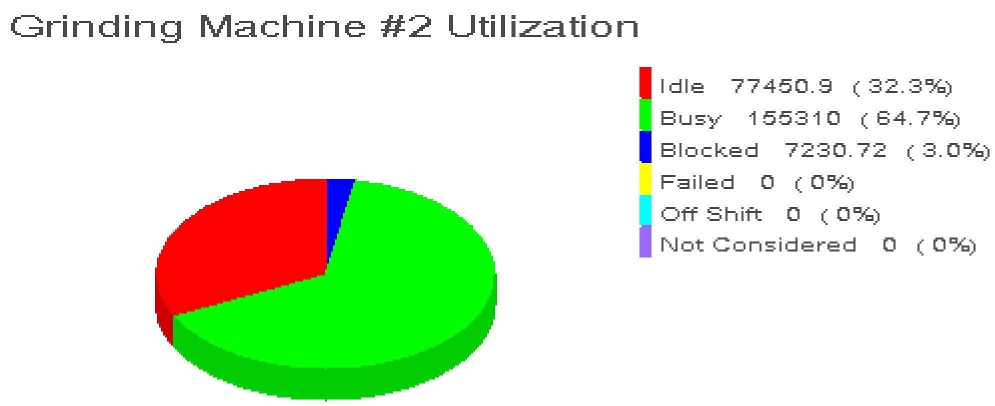


Fig. 7.10. Grinding Machine #2 Utilization.

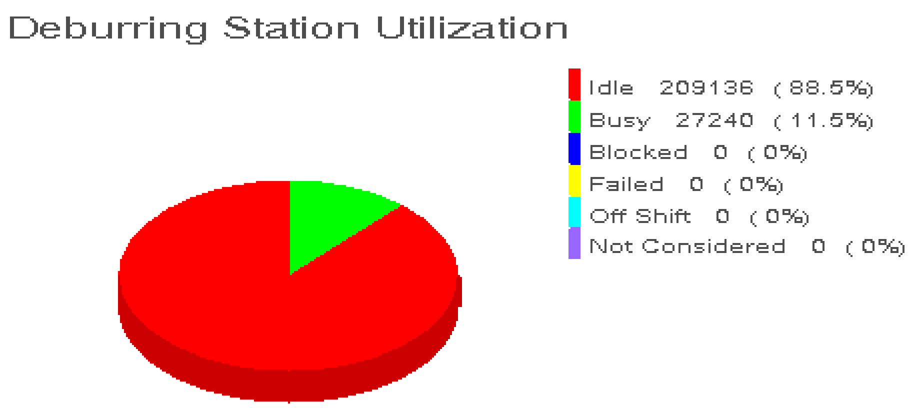


Fig. 7.11. Deburring Station Utilization.

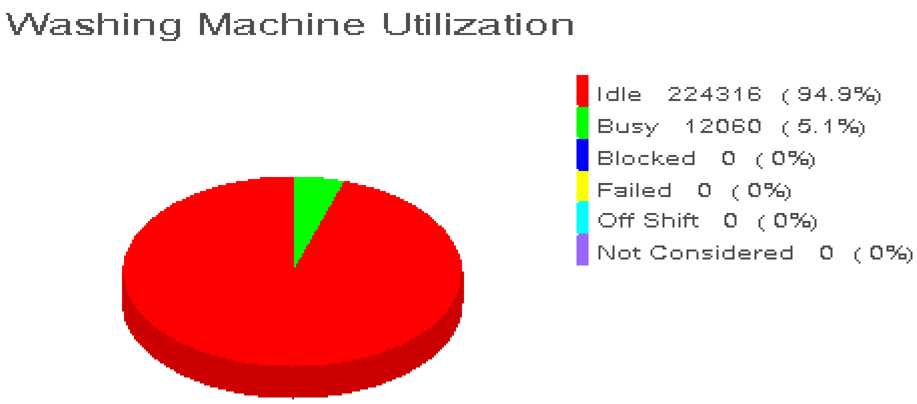


Fig. 7.12. Washing Machine Utilization.

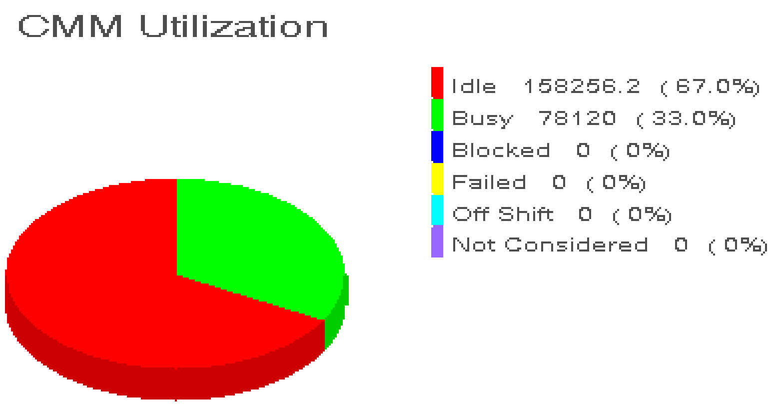


Fig. 7.13. CMM Utilization.

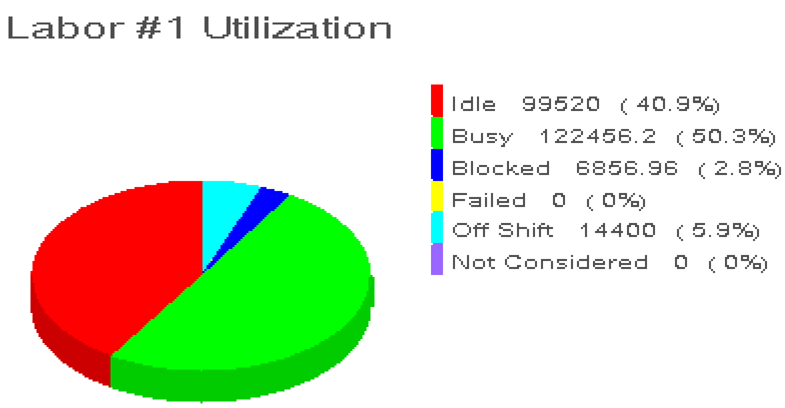


Fig. 7.14. Labor #1 Utilization.

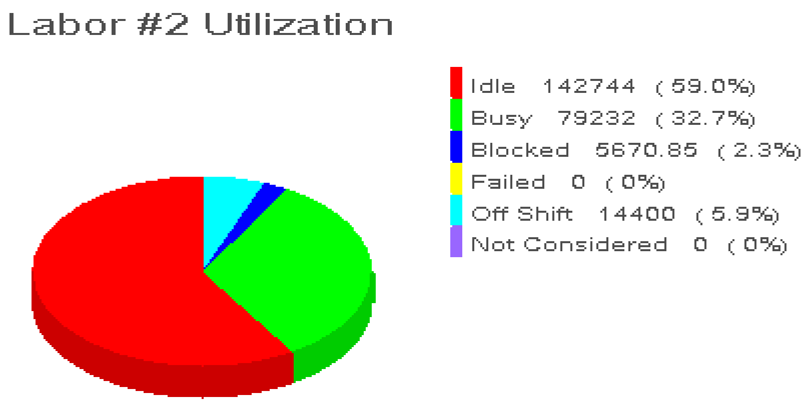


Fig. 7.15. Labor #2 Utilization.

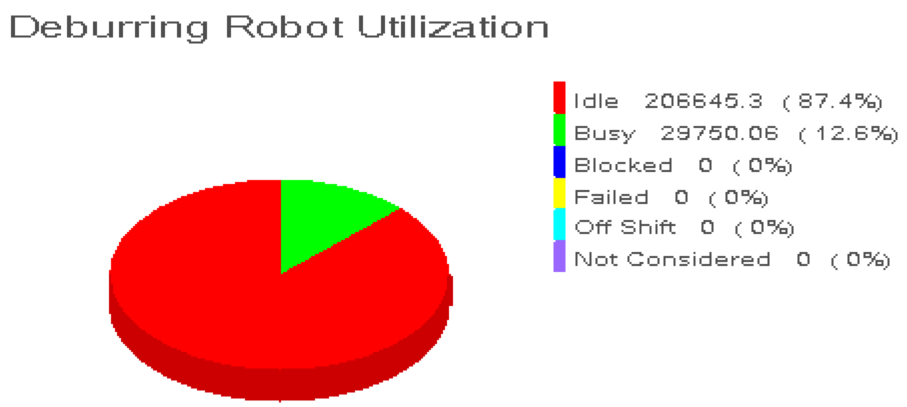


Fig. 7.16. Deburring Robot Utilization.

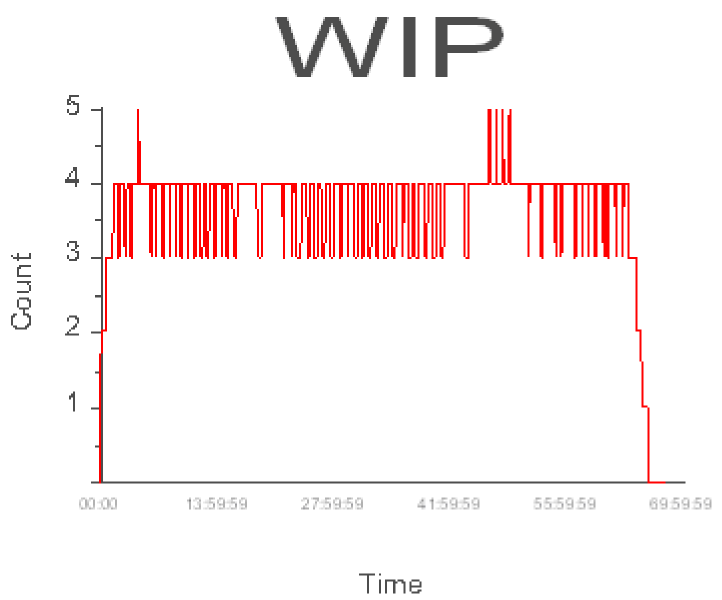


Fig. 7.17. Number of parts contemporarily inside the manufacturing cell.

Fig. 7.17 shows the number of parts inside the robotic manufacturing cell during the simulation: the maximum number of parts contemporarily in the system is 5.

By running the model of the manufacturing cell, it was possible to have a visual representation of the cell's functioning, allowing to verify if all the logics and connections have been properly set. Moreover, for each simulation run, detailed information regarding all the elements of the model and the processes carried out in the system were provided.

In order to analyse the behaviour of the manufacturing cell, it is interesting to analyse the data regarding the total production time, the utilization of machines and the labors busy and idle time. The total time required to produce an entire kit of vanes in the actual configuration of the cell is 3940 min. Daily production in the plant is organised in 3 shifts each consisting of 8 hours, for 6 days a week (considering that there is no production on sunday). This means that, with the current configuration of the manufacturing cell, the production of an entire kit, composed of 67 parts, requires 9 work shifts.

In Table 7.5, the utilization of all the elements in the system, i.e. machines as well as labors is reported as percentage of busy time over the total production time for 1 complete kit.

Element	Utilization (%)
Machine 1	89
Machine 2	65
CMM	33
Deburring	11
Washing	5
Labor 1	51
Labor 2	33

Table 7.5: Utilization of machines and labours in the existing cell

The element showing the highest utilization is the grinding machine #1, with 89% busy time. This utilization is very high, and it cannot be further increased. None of the elements shows a utilization near to 100%, even if machine faults, or programmed maintenance has not been considered in this model. This is because in this simulation, the system is considered initially empty, in order to evaluate the production of an entire kit. Moreover, the manufacturing cell includes 2 labors, who don't work incessantly during their shift, but need some breaks during the day. Six breaks per shift have been introduced in the model, and the break time spent by each labor during the time of the simulation is known and reported in Table 7.6.

Labor	Shift - Break time (min)
Labor 1	210.0
Labor 2	210.0

Table 7.6: Shift - Break time for the labors.

7.4 ENHANCEMENT OF THE MANUFACTURING CELL

7.4.1 POSSIBLE AREAS OF IMPROVEMENT

By analyzing the simulation results, several possible issues were indentified to improve the productivity and efficiency of the manufacturing cell through its reconfiguration.

The bottleneck of the system is easily identified as the element having the highest utilization, i.e. the machine #1, (this is because the cycle times of machining operation 1, to be added to the mounting and dismounting times of parts on fixtures, are very high). The elevated busy time of this machine indicates that the productivity of the whole system can only be increased by acting on the operations carried out on this element.

The immediate solution would appear to purchase a further machine tool to perform the required operations in parallel: this solution is unfeasible for the company, as it would involve a huge economic effort and layout problems, since these kind of machines are very expensive and cumbersome.

Other solutions should be then imagined to increase the efficiency of the manufacturing cell. An interesting consideration is that mounting and dismounting of parts and fixtures, required to carry out the machining operations, are performed by a human operator on the machine tools, requiring additional busy time on the machines. An alternative to this could be to export mounting and dismounting operations outside the machines. This means that parts are mounted on the proper fixtures on a separate mounting table, where the labor can perform mounting/dismounting in an easy way and without working on the machine. However, a new problem is generated by this configuration: once a part is mounted on the fixture it cannot be moved by a human labor, since the resulting assembly is too heavy. It would be then necessary to introduce a new handling system, such as a robot capable of moving parts and fixtures throughout the cell and loading/unloading parts on the different machines. In such a way, the number of human operators in the cell would be reduced to one, only dedicated to mounting/dismounting of parts and fixtures, while all the transporting tasks would be committed to the robot. This solution could be interesting since, in general, automated machine load/unload can provide benefits including higher throughput, improved process flow (because of predictable cycle times), reduced product damage (because of controlled handling) and consistent run speeds with no breaks, shift changes or retires.

However, the introduction of the robot as new handling system for the manufacturing cell requires further design and analysis before its implementation, since material handling systems are often costly and can have many potential risks. There are several complex design, operational and scheduling issues that need to be addressed for successful implementation. Simulation technology can be used to better analyse the system before its implementation.

The main advantages of the employment of simulation in this case are:

- Avoid costly mistakes, by verifying and improving the design and operational rules of the material handling system (the robot in our case study) before its installation.
- Choose the right material handling system specific to your system
- Test-bed to improve design and operational rules and implement new systems
- Integration of the material handling system with other devices
- Estimate crucial parameters
- Experiment on model rather than actual system
- Visualization and communication

Simulation plays an important role in all the phases of a manufacturing system project involving a new automated material handling system: conceptual phase, detailed design phase, launching phase and fully-operational phase (Ramirez Cerda, 1995).

1. Conceptual phase

The conceptual design phase is the phase where the physical system is not actually put into place. The principal objectives of applying simulation to the conceptual phase are:

- Evaluate/justify the need for automation.
- Estimate the type and level of automation required.
- Visualize the proposed system.
- Communicate ideas to the management and engineers.

Using Discrete Event Simulation in this phase allows to evaluate a proposed design before attempting the subsequent design phases. The goal is to achieve a reasonable, if not optimal, system capable to produce the needed product in the desired manner.

2. Detailed design phase

If the conceptual phase gives advice to proceed with the project, the detailed design phase begins. Extensive design plans are developed for all the issues that have to be addressed, including the layout design, equipment design and justification cycle time verifications, operational, scheduling and dispatching issues and integration of material handling system with other systems. The simulation engineer develops a base model for the entire system which includes the process system logic (e.g., machines, part routings, operator logic) and the material handling system logic (e.g., carriers, conveyors, routing and scheduling of the movement system logic). The simulation model developed captures the stochastic nature of the system and the dynamic interactions among the various subsystems, thereby making it a very powerful for decision making. The base model undergoes numerous iterations before the desired system specifications are attained.

The principal objectives of applying simulation to the detailed design phase are:

- Layout design.
- Material handling design and justification.
- Cycle time verifications.
- Movement system operational and scheduling issues.
- Integration of material handling system with other systems.

The principal factors considered here include layout design (e.g., path design, size and location of buffers and machines), material handling design and justification (e.g., robot model, rail length), cycletime verifications (e.g., robot and rail speeds), movement system operational and scheduling issues, and integration of material handling with other systems such as other material handling systems and operators (e.g. in order to avoid collisions). 3D simulation software tools can be employed in this phase, since they have motion capabilities suitable for this category of analysis.

3. Launching phase

The launching phase refers to the phase where the manufacturing system operates under the designed conditions before ramp-up. Simulation studies at this stage are generally used to test operational policies (e.g., test different path selection rules, dispatching rules) and integration of material handling with other systems such as other material handling systems and operators.

4. Operational phase

The fully operational phase refers to the phase where the plant is operating under full capacity conditions. The simulation studies done at this phase consider the impact of factors such as product mix decisions, new product introduction, new operational policies, and line modifications on the throughput of the existing material handling system.

Fig. 7.18 shows the application of simulation to the four phases of a material handling project.

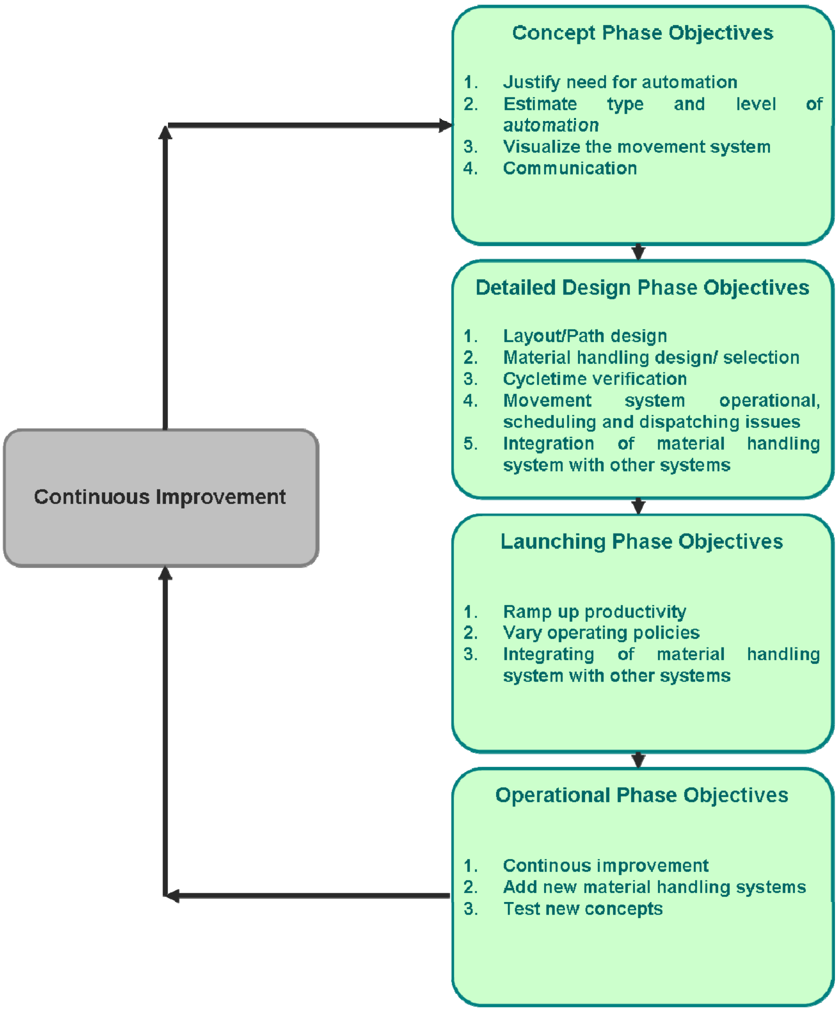


Fig. 7.18. Application of simulation to the four phases of a manufacturing system project involving automatic material handling device.

7.4.2 New DES Model

As illustrated in the previous paragraph, deep analysis is needed to verify the feasibility and the expected positive effects of the changes before the actual implementation of the proposed upgrades in the manufacturing cell.

Since the current phase of the manufacturing system reconfiguration process is still conceptual, discrete event simulation is helpful to support decision making. For this purpose, the proposed modifications in the manufacturing cell were simulated through the DES software DELMIA QUEST to analyze the production flow and the performance of the cell.

The new model was built on the basis of the previous one, but required some considerations. First of all, an assembly table was introduced in the model, to provide a place outside the machines where all the mounting and dismounting operations are performed. This solution involved also the presence of a further buffer containing the fixtures on which the parts should be mounted. The mounting table was connected to the input storage of parts and the fixture storage as well as to the machine tools and the CMM.

The scheme of the reconfigured manufacturing cell is shown in Figure 7.14, while its components are summarised in Table 7.7.

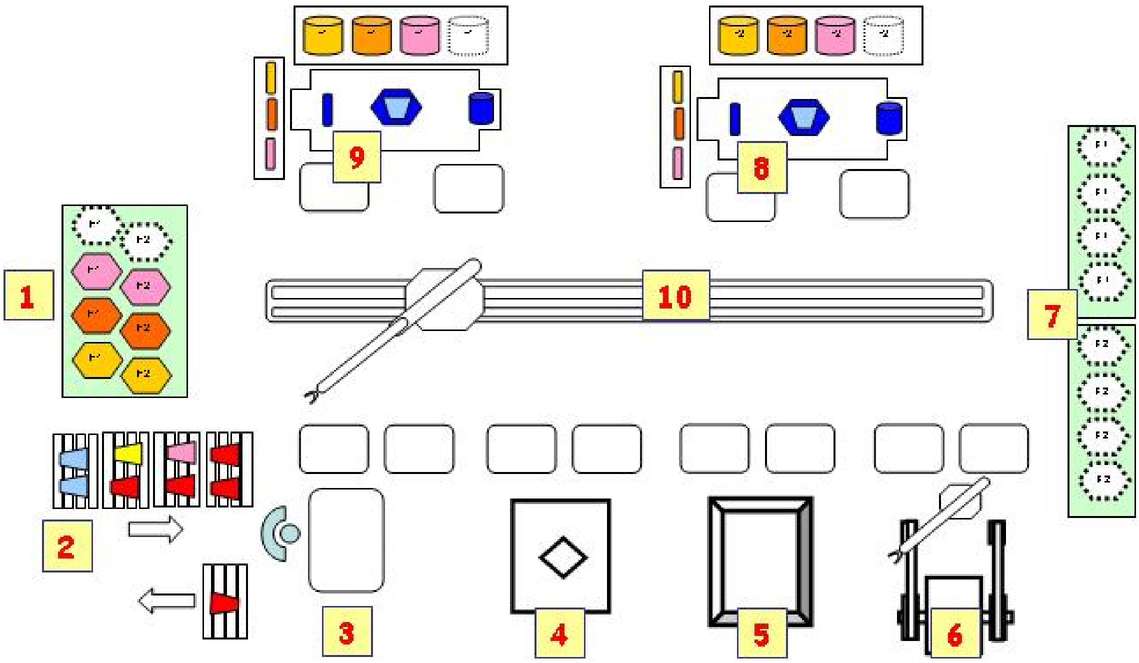


Fig. 7.19. Scheme of the reconfigured MC.

N.	Manufacturing Cell Component
1.	Fixtures Buffer
2.	Input/Output Vanes Buffer
3.	Vane/Fixture Assembly Workbench
4.	CMM – Coordinate Measuring Machine
5.	Washing Station
6.	Automatic Deburring Station
7.	Intermediate buffers for vanes mounted on fixtures
8.	Grinding Machine 1
9.	Grinding Machine 2
10.	Handling Robot

Table 7.7. Manufacturing Cell Components.

The sequence of operations carried out in the new cell is summarized in Table 7.8. The parts - coming from the input buffer - are mounted on the proper fixtures - coming from the fixture buffer - on the mounting table by the Labor 1, who is the only human labor in the cell. Labor 2 was substituted by a robot, used for material handling of both parts and fixtures

Part	Process	Product
NGV1_Raw1 Fixture1	Mounting_1	NGV1_Fixt1
NGV1_Fixt1	Grinding_1	NGV1_Fixt1_grinded
NGV1_Fixt1_grinded	Measuring_1	NGV1_Fixt1_measured
NGV1_Fixt1_measured	Dismounting_1	Fixture1 NGV1_Raw2
NGV1_Raw2 Fixture2	Mounting_2	NGV1_Fixt2
NGV1_Fixt2	Grinding_2	NGV1_Fixt2_grinded
NGV1_Fixt2_grinded	Cleaning	NGV1_Fixt2_cleaned
NGV1_Fixt2_cleaned	Deburring	NGV1_Fixt2_deburred
NGV1_Fixt2_deburred	Washing	NGV1_Fixt2_washed
NGV1_Fixt2_washed	Measuring_2	NGV1_Fixt2_measured
NGV1_Fixt2_measured	Dismounting_2	NGV1_Final Fixture2

Table 7.8 Parts, processes and products.

The introduction of the robot required attention in order to consider the differences with respect to a human labor. First of all, the movement of the robot is slightly different from that of a human labor, since it is constrained to walk on a predefined path system, represented as the yellow line in Figure 3. From this path system, the robot will be able to rotate its arm and reach the desired buffer or machine with its tip. Another aspect is the speed of the robot: at this stage, deep information is not available, since the robot model and other specifications have not been defined yet, so that speed was set to 13 m/min on the basis of generic data on the characteristics of common industrial robots. This speed of movement is not very high, but the real advantage of using a robot is obtained in the fitting of parts on a machine tool: this time is generally reduced if compared to a manual loading system. The time required for loading/unloading processes of parts in the new model was then reduced taking into account the capability of the robot.

The simulation model of the upgraded manufacturing cell is shown in Figure 7.15, where the components are numbered following the scheme of Table 7.9.

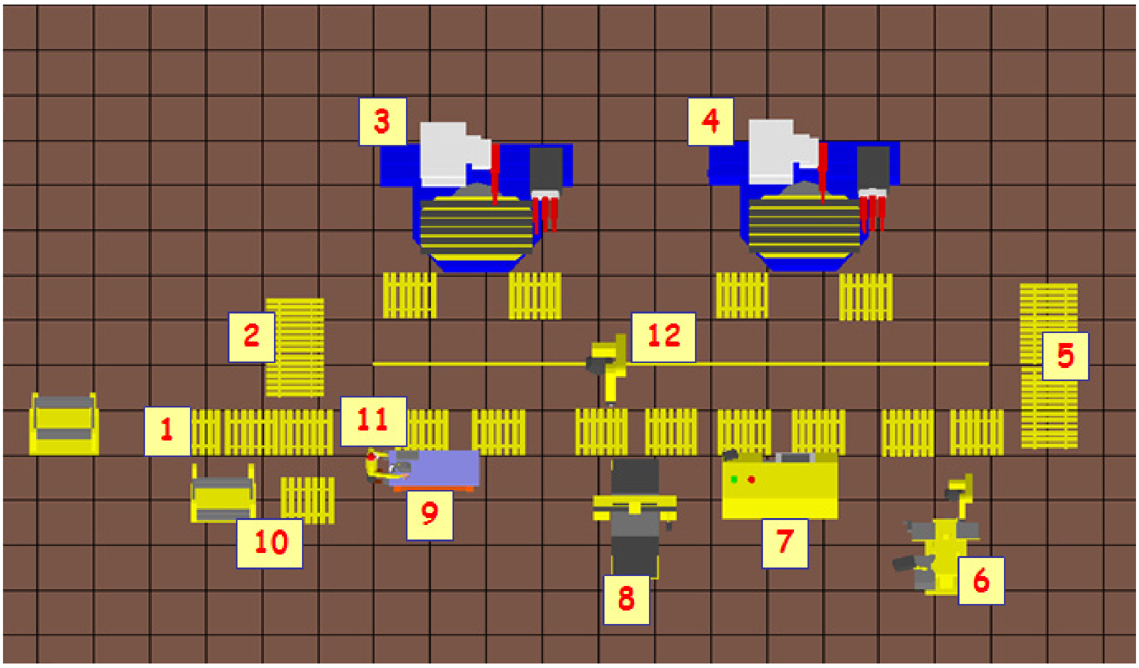


Fig. 7.20. Virtual model of the new manufacturing cell

N.	Name of Component
1.	Input Storage
2.	Fixture Storage
3.	Assembly Table
4.	Machine #1
5.	Machine #2
6.	Intermediate Storage
7.	Deburring Machine
8.	Washing Machine
9.	Coordinate Measuring Machine (CMM)
10.	Output Storage
11.	Labor 1
12.	Robot

Table 7.9: Components of the new manufacturing cell.

7.4.3 New DES Results

Simulation was carried out on the new manufacturing cell model, in order to evaluate the effects of the modifications introduced in the system. The data generated by this simulation showed that the total time required to produce an entire kit was 4923 min, i.e. 82 hrs (11 work shifts), that is higher than the previous case. It is important to notice that the model employed for this simulation is not sufficiently accurate to evaluate the total production time in a reliable way, since data on the robot are not very precise. However, this simulation is very helpful in order to verify the difference in the utilization of all the system elements, i.e. machines as well as the labor and the robot, that are reported in Table 7.10 as percentage of busy time over the total production time for 1 full kit.

Element	Utilization (%)
Machine 1	57
Machine 2	38
CMM	26
Deburring	9
Washing	4
Mounting Table	21
Labor 1	32
Robot	22

Table 7.10: Utilization of machines and labours in the new cell - 1 fixture of each type.

From the analysis of Table 7.10, it appears that the utilization of machines 1 and 2 is much lower if compared to the already existing manufacturing cell, and a better balancing of the utilization among the different machines has been obtained. The advantage offered by the new configuration of the manufacturing cell is a greater flexibility. In fact, the presence of a mounting table external to machines and a buffer containing the required fixtures, gives the opportunity to introduce in the system as many fixtures as desired (with the only constraint related to the capacity of the fixture buffer). The consequence of this is significant: in fact, by increasing the number of fixtures available for each type of part/operation, mounting and dismounting operations can be carried out on the mounting table in parallel to the machining operations on machine tools #1 and #2. Working in parallel should certainly reduce the total production time, and increase the utilization of machines, robot and labor. To evaluate the effect of the introduction of further fixtures, a new simulation was carried out with a number of fixtures increased to 12 (2 identical fixtures of each type).

The first interesting datum produced by this simulation is the total time required to produce an entire kit: it was reduced to 3178 min, i.e. 53 hrs (7 work shifts). If compared to the total production time of the real manufacturing cell, it provides a decrease of 11%. Moreover, in terms of work shifts, it requires 7 shifts instead of 9. As regards the utilization of all the elements in the system, in Table 7.11, the utilization of all the machines as well as the labor and the robot is reported as percentage of busy time over the total production time for 1 full kit.

Element	Utilization (%)
Machine 1	88
Machine 2	59
CMM	40
Deburring	14
Washing	6
Mounting Table	33
Labor 1	50
Robot	39

Table 7.11: Utilization of machines and labours in the new cell - 2 fixtures of each type.

By comparing this table to the previous ones, two remarks can be made. First of all, the utilization of all the elements in this simulation is considerably increased with respect to the case where only 1 fixture was introduced in the system: this is because machine tools and mounting table can now work in parallel, and the total production time is reduced. Moreover, even if the total production time is lower than that of the real cell (3178 min instead of 3940 min), the utilization of the bottleneck machine, i.e. grinding machine #1, as well as that of the machine #2, is lower than in the real cell. The reason of this result is that the introduction of the mounting table has produced a more homogeneous distribution of load among the machines of the manufacturing cell. The utilization of grinding machine #1 and #2, that was too high before, is now decreased, while the utilization of the CMM, the deburring and the washing machines, that was very low, is now slightly increased.

By further increasing the number of fixtures available in the cell, an additional decrease of the total production time will be encountered. However, this decrease will be less and less significant, until the condition when a higher number of fixtures will not positively affect the total production time. This is because, at a certain point, the utilization of machines will be already saturated, and the parts mounted on fixtures will be collected on the intermediate buffers waiting to be processed by the machine tools.

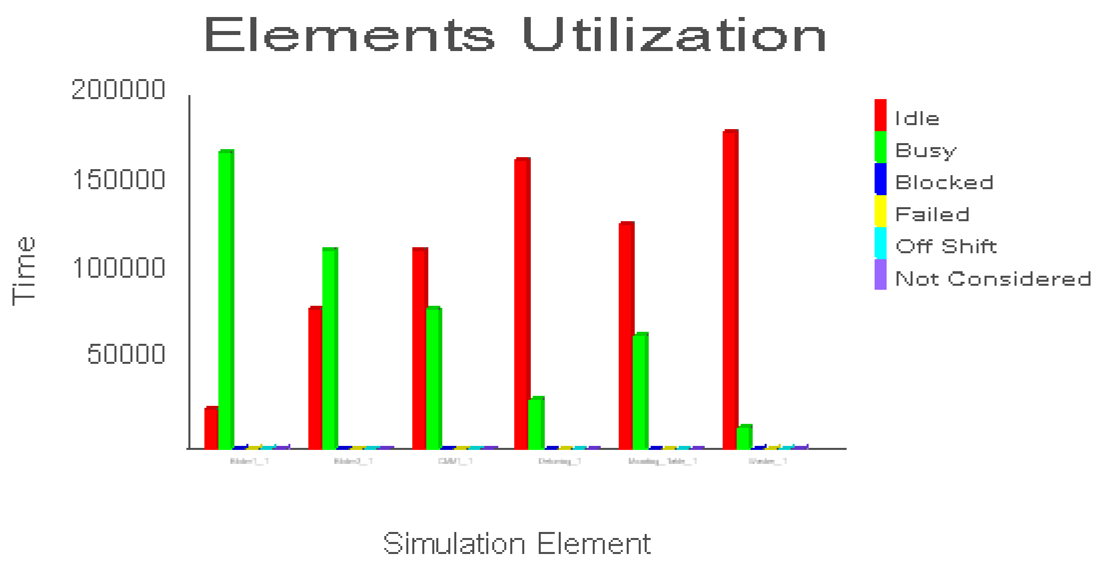


Fig. 7.21. Elements utilization.

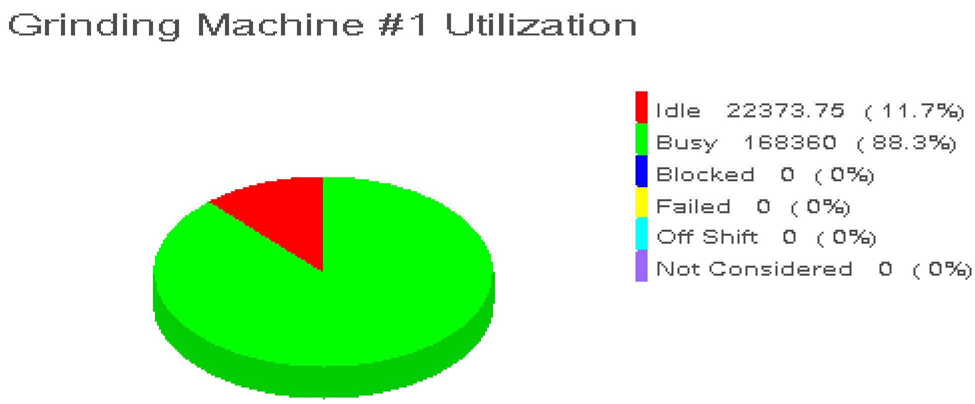


Fig. 7.22. Grinding machine #1 utilization.

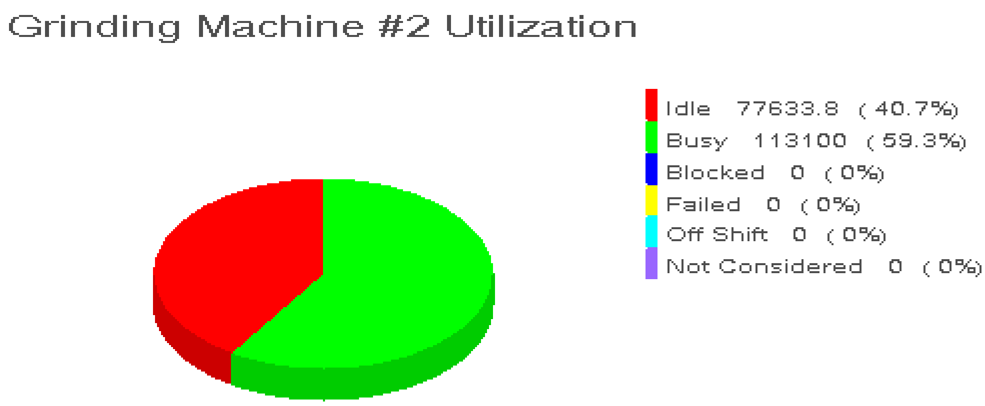


Fig. 7.23. Grinding machine #2 utilization.

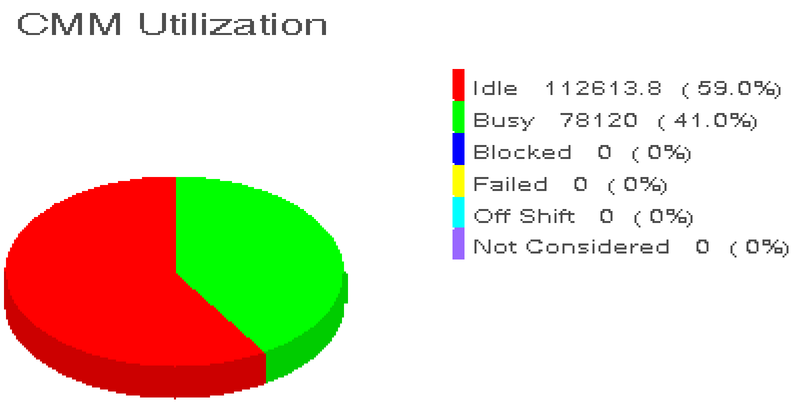


Fig. 7.24. CMM utilization.

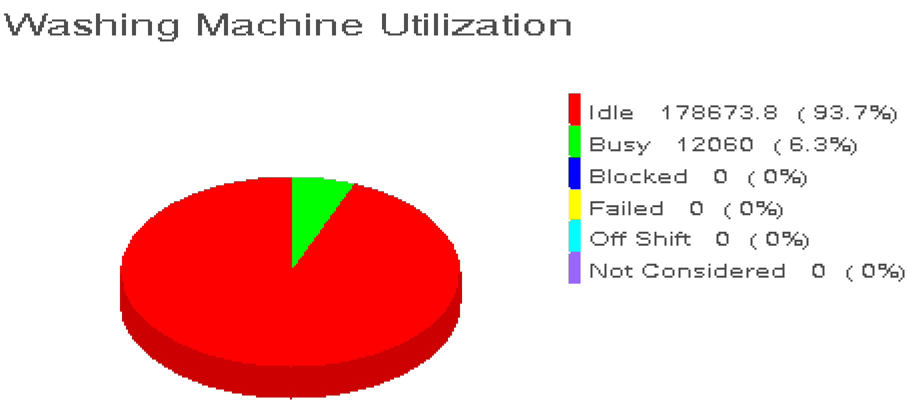


Fig. 7.25. Washing machine utilization.

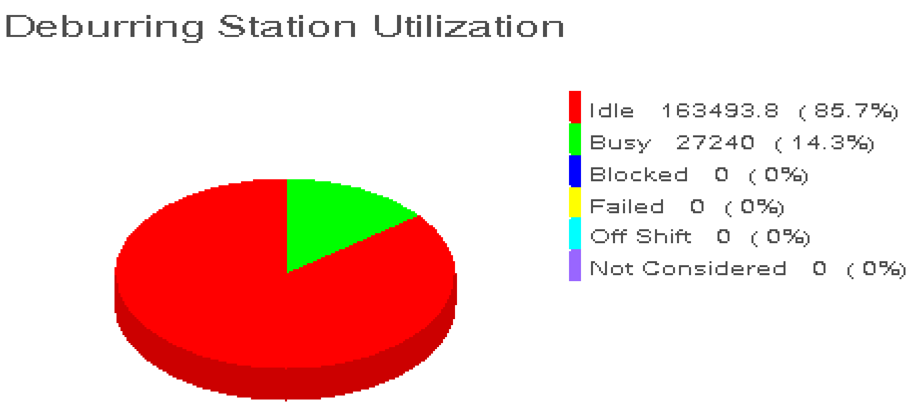


Fig. 7.26. Deburring station utilization.

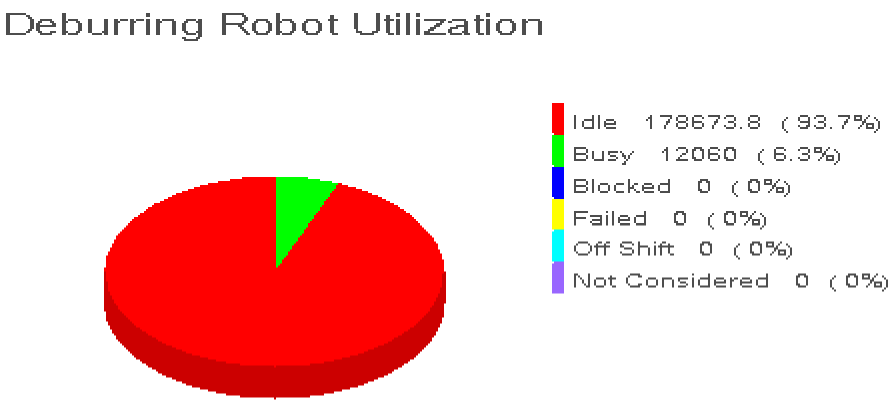


Fig. 7.27. Deburring robot utilization.

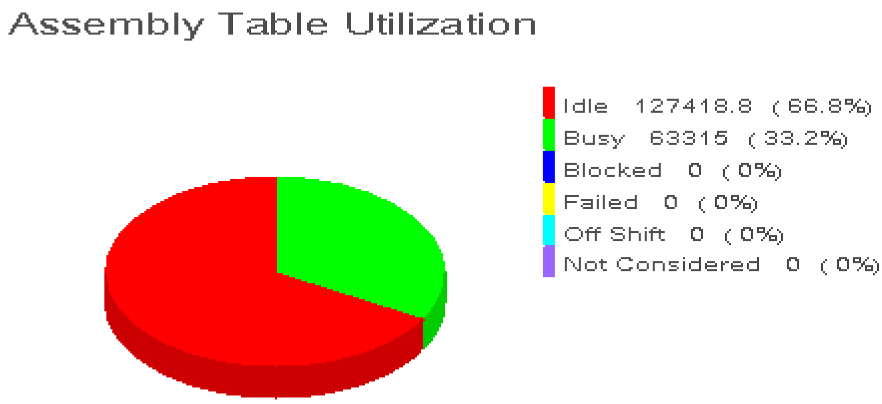


Fig. 7.28. Assembly table utilization.

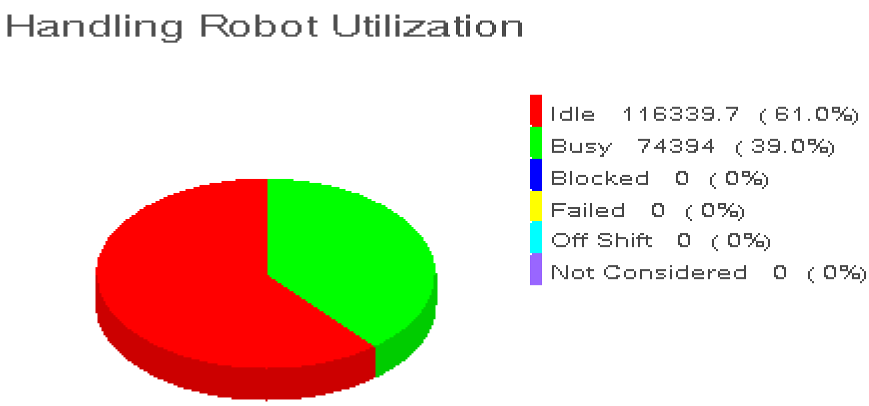


Fig. 7.29. Handling robot utilization.

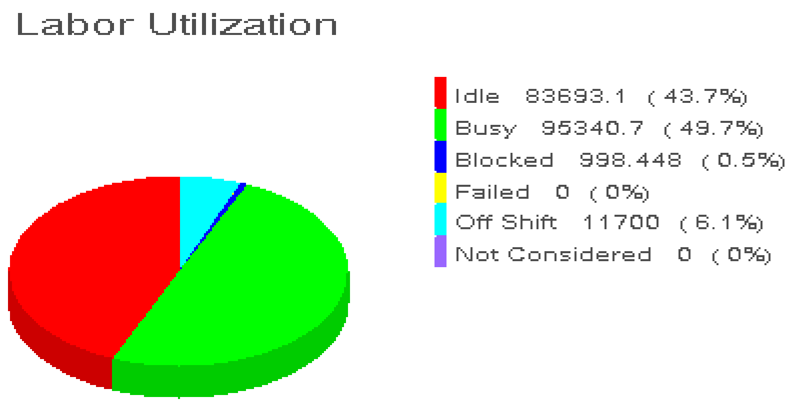


Fig. 7.30. Labor utilization.

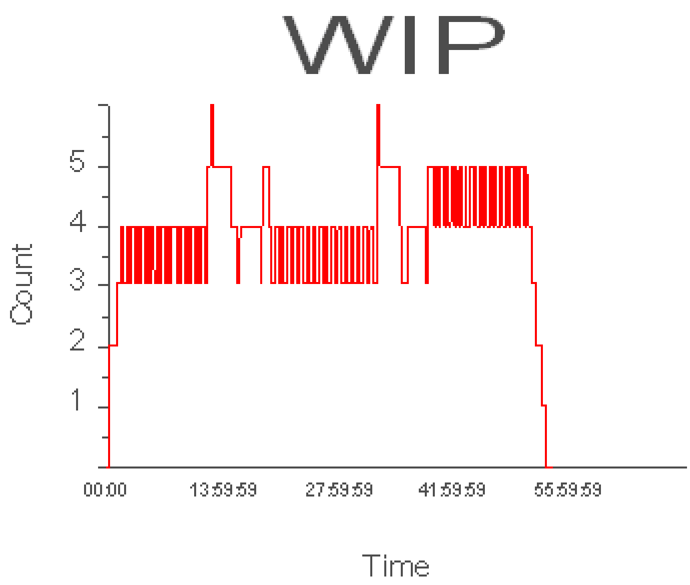


Fig. 7.31. Number of parts in the system.

7.4.4 DES SUMMARY

The digital model of an existing manufacturing cell was simulated to examine the system's performance in terms of utilization of the available facilities, bottleneck of the system, busy and idle time of labors. The numerical and visual analysis of the system's production flow suggested several possible areas of improvement to increase the productivity of the manufacturing cell. In particular, a solution involving the utilization of fixtures external to machines, and the use of a robot for fixture and vane handling was proposed. In order to verify the consequences of these modifications on the system's performance, a simulation of the new cell was performed. The simulation demonstrated that the external fixture utilization can help reducing the machine busy time: in order to carry out mounting and dismounting operations during machine working, and reduce the total production time, though, it was necessary to introduce further fixtures for machining.

These changes, applied to the virtual model of the manufacturing cell, provided the following advantages:

- Reduction of loading and unloading time.
- Convenient handling and shifting of heavy fixtures.
- Reduction of labor involvement in material handling.
- Flexibility to use any desired number of fixtures (offered by the utilization of an external mounting table).
- Increase of machine availability by avoiding the mounting time on machine attached fixture.
- Reduction of total production time for the completion of 1 full kit .

7.5 CONSIDERATIONS

The application of DES for the manufacturing system simulation in the conceptual phase of the reconfiguration process allowed to evaluate the proposed solution before attempting the subsequent phases of the MC design. The obtained results encouraged to proceed with the detailed design phase of the project, to carry out further investigation activities.

A deeper analysis is then required to investigate the feasibility of the introduction of a robot as new material handling system, in terms of layout design, equipment design and integration of material handling system with other systems: reachability of all the targets, safety of movements and layout reconfiguration should be issued. In this phase of the project, DES is not sufficient to evaluate all the required aspects, and the employment of a 3D simulation software becomes necessary.

7.6 3D SIMULATION OF THE ROBOTIC MANUFACTURING CELL

The additional analysis of the manufacturing cell was carried out through the 3D simulation software DELMIA V5, whose main features have been described in Chapter 6.

7.6.1 MANUFACTURING CELL 3D MODELLING

Unlike DES, where mostly logics, cycle times and distances are relevant, 3D motion simulation requires an in-depth analysis of geometrical and functional features of machines, equipments and material handling systems. The following data must be collected in order to set-up a valid model for the 3D motion simulation:

- Exact geometry and real dimensions of all the machines
- Detailed model of part and fixtures
- Realistic model of the robot and the rail to be employed, including kinematics features
- Mechanisms for all moving devices (in order to simulate motion)
- Sequence of operations

Models can be created on the basis of available libraries, through design within the software environment, or by importing already existing CAD files.

Kinematics modules can manage computation for robot kinematics, and collision detection modules are able to sense collisions among moving surfaces.

This category of simulation can be suitably employed in the design of a material handling system such as a robot, to verify material handling layout and path, and assess the integration with other handling systems, equipment and operators (Ramirez Cerda, 1995).

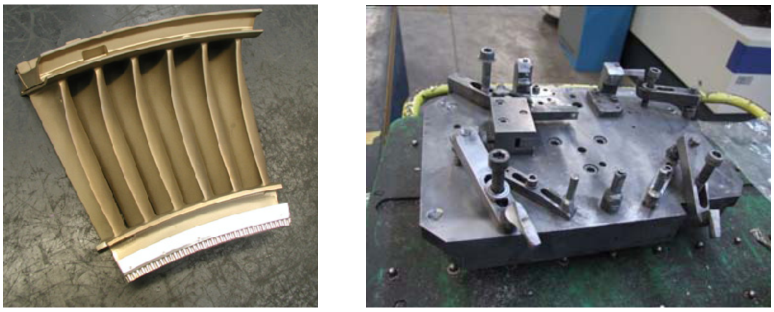
To realise a 3D model of the cell for the simulation activity being the nearest possible to the real characteristics of the cell, it is necessary to create 3D models of all the elements involved in the cell, i.e. parts, fixtures, machines, buffers, etc.

On the basis of the starting scheme, the detailed study of the cell requires an in-depth examination of the constraints and the geometrical and functional features of the machines and all the other equipments.

In order to acquire the data concerning the features, geometry and dimensions of the manufacturing cell components, a survey was carried out at the Avio facility of Acerra.

PARTS AND FIXTURES

The vanes produced within the manufacturing cell are turbine vanes, similar to that shown in Fig. 7.32. These vanes are characterised by thin surfaces: their clamping on the fixtures may introduce distortions that would compromise the machining result and consequently the product quality and acceptability, thus a fixture with a high precision positioning system must be employed. The weight of such fixture is about 45 Kg, whereas parts maximum weight is 2,5 Kg. In the first grinding phase, the part is positioned on the fixture on a datum point defined on the casting parts. In the second grinding phase, the part is positioned on the first phase machined surfaces. Parts and fixtures are similar to those shown in Fig. 7.32 a-b.

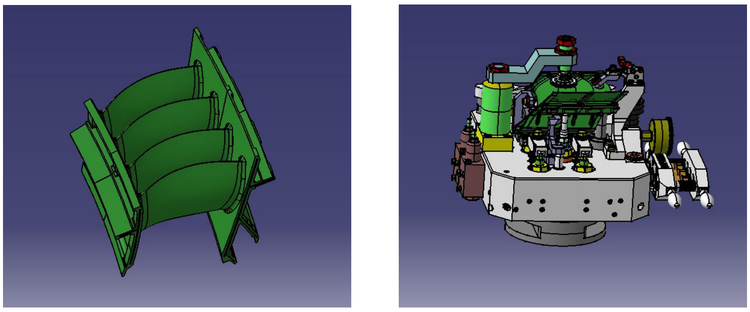


(a) (b)

Fig. 7.32. (a) Part. (b) Fixture.

3D models of a NGV1 vane and its fixture, shown in Fig. 7.33 a-b, were imported in the 3D software Delmia V5. The CAD files were imported as IGES (Initial Graphics Exchange Specification) files and then saved in the .CATProduct format, in order to be employed within the simulation software.

On the left and right side of the fixture base there are two grooves to allow the robot handling tool for grabbing and holding.



(a) (b)

Fig. 7.33. 3D model of: (a) part. (b) part mounted on its fixture.

As concerns the other components of the cell, the physical measurement of the equipments currently available in the plant was necessary. In the following paragraphs, the features obtained during the survey carried out at Avio facility of Acerra are reported.

The other components of the cell were designed within the software environment with particular attention to their overall size and to the details of the working zone, where the robot needs to access for part loading/unloading.

ROBOT

Since the robot model has a central role in this simulation, it was carefully set up on the basis of the real robot to be employed in the MC. The robot selected for material handling is the 6 axes KUKA KR100-2 P that can perform handling, loading and unloading of very heavy loads (payload is about 100 kg, supplementary load 50 kg). The dimensions of this robot are rather large, with a maximum reach of 3500 mm and a weight of 1500 kg; its repeatability is <±0,2 mm. A realistic 3D model of this robot was acquired from DELMIA V5 software database, containing not only the geometrical features, but most importantly the kinematics of the real robot, as shown in Fig. 7.34.

The robot itself is not provided with a grasping device: a gripper for the robot, adequate to handle the available fixtures, has been designed by the company engineers and its 3D model is shown in Fig. 7.35. This gripper is similar to a fork, so it can grab the fixture by inserting its prongs in the two grooves of the fixture base. The movement required to draw a part from a machine is a horizontal translation to fit the grooves and a vertical movement to raise the part. The configuration of the gripper/fixture couple requires the robot to keep its hand horizontal while moving a fixture; this constraint is not active when the gripper is empty.

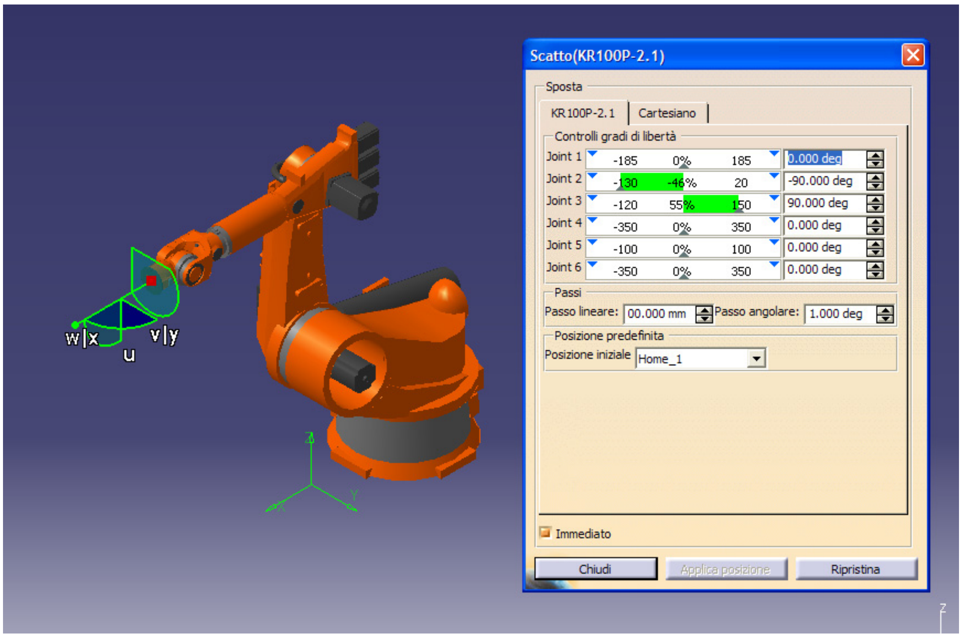


Fig. 7.34. 3D model of the KUKA KR100-P Robot.

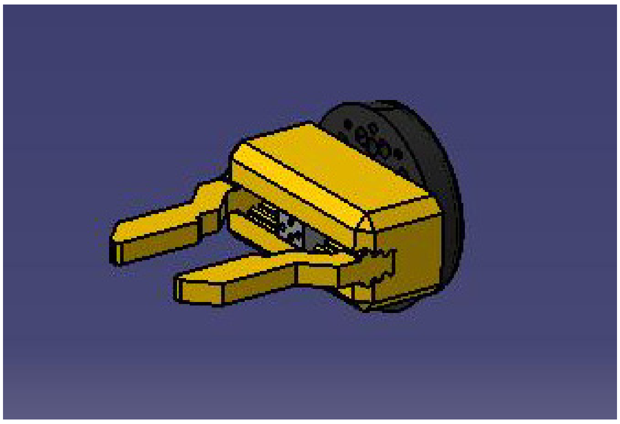


Fig. 7.35. 3D model of the gripper for fixtures handling.

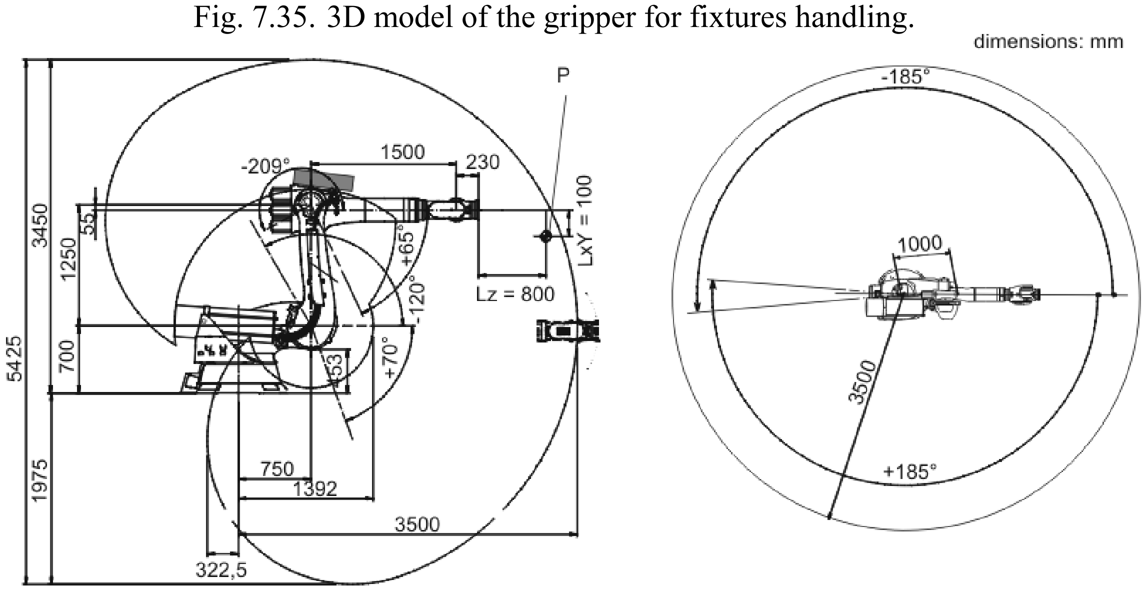


Fig. 7.36. KUKA KR100-P workspace envelope from the technical data sheet.

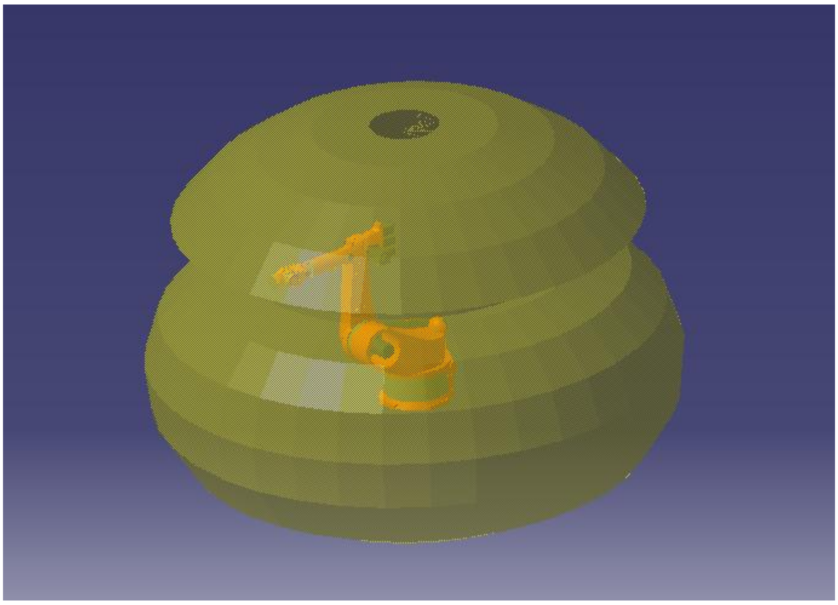


Fig. 7.37. KUKA KR100-P workspace envelope generated through the simulation software.

By assuming that the KUKA KR100-P is on a fixed position on the floor, the workspace of the robot can be represented as in Fig. 7.36-7.37. This figures show all the points that can be reached by the robot from that position: it is to notice that there is not only a maximum, but also a minimum distance that a target should have from the robot. To reach all the targets spread throughout the cell, the robot should be placed on a linear unit, with a proper length sufficient to reach all the objectives. The linear unit KUKA KL1500-2 was selected within the KUKA rail catalogue as designed for the specific robot selected for the MC. As regards speed, technical data on the rail indicate a maximum translation speed of 1.45 m/s and this value was introduced in the simulation software for the rail movement. As concerns the robot, on the other hand, speed for joints movement was set in the robot model.

Fig. 7.38. Robot on the rail.

MACHINE TOOLS

In order to examine the dimensions of the grinding machine tools and to highlight the areas of these machines that the robot should reach for workpiece positioning, a survey was carried out on the grinding machine tool available at the facility of Acerra.

The grinding machine is a BLOHM PROFIMAT, characterised by the following technical specifications:

- 5 axes numerical control grinding machine
- Ceramic wheel & diamond rolls
- HSCD High Speed Continuous Dressing (the diamond roll dresses the wheel during the machining process, as shown in Fig. 7.39)
- Automated change of the grinding wheel
- Working volume (mm) X= 1000, Y=500, Z=550
- Accuracy: ±2 µm
- Siemens control suitable for linking with the company information system
- CIMTEC A3 Coolant

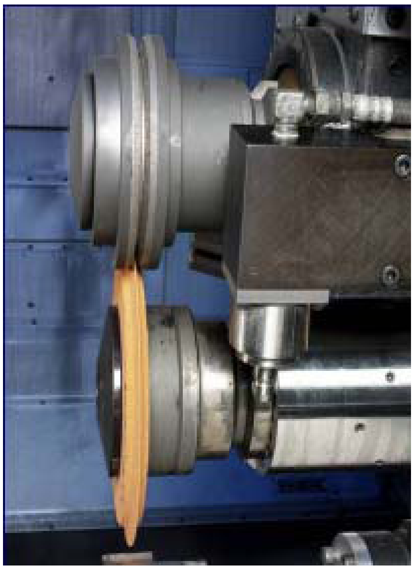


Fig. 7.39. HSCD High Speed Continuous Dressing.

The grinding machine is provided with a wide area dedicated to tools storage, containing different types of grinding wheels depending on the vane stage and the machining phase. Fig.7.40 shows the machine tool and the related storage area.

Fig. 7.40. Grinding Machine Tool.

On the floor, located in the front of the machine tool a platform must be placed, with height of 150 mm and depth of 1000 mm: the platform dimensions have been taken into consideration because they could represent a constraint for placing the rail-mounted robot.

Other important details concerning this machine tool are related to the height and width of the front door through which the workpiece will be introduced for machining. Fig. 7.25 shows how the parts are positioned on their support inside the grinding machine.

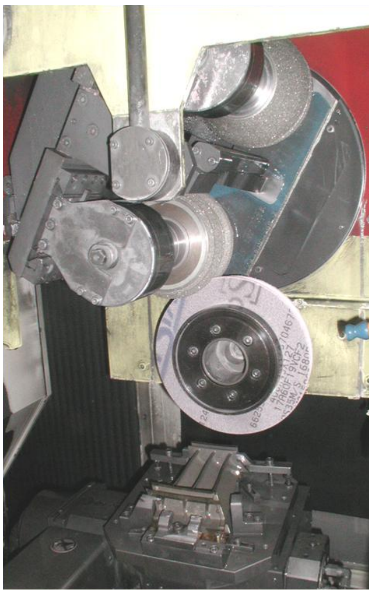
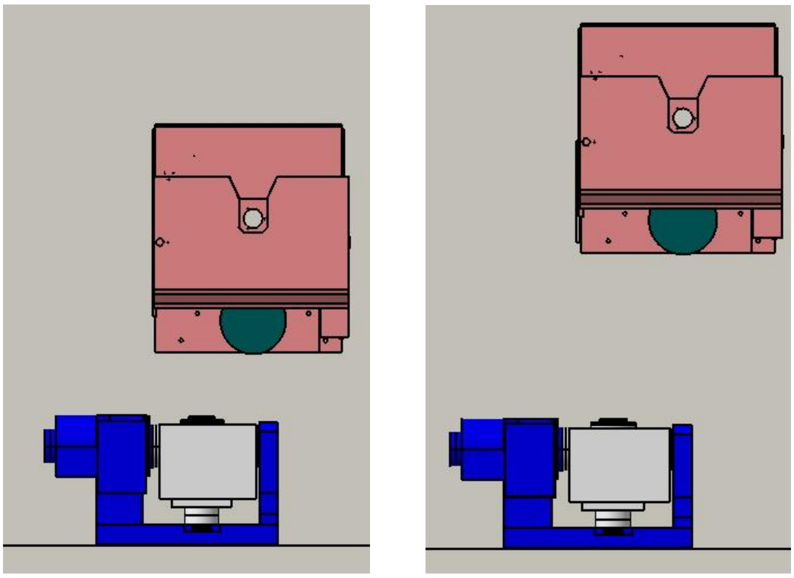


Fig. 7.41. Grinding wheel and workpiece support.



(a) (b)

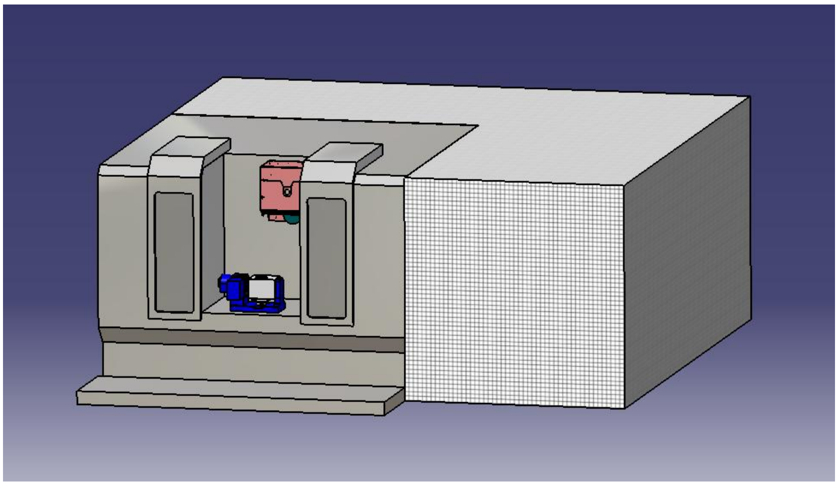
Fig. 7.42. 3D models of the grinding tool and the workpiece support: (a) Down. (b) Up.

As regards the grinding wheel inside the machine and the workpiece support table, IGES files of both elements have been provided by the company, as shown in Fig. 7.26 a-b. The support consists of a main block with an ISO cone that allows for an extremely precise positioning of the fixture, since the latter has a corresponding cavity on its base.

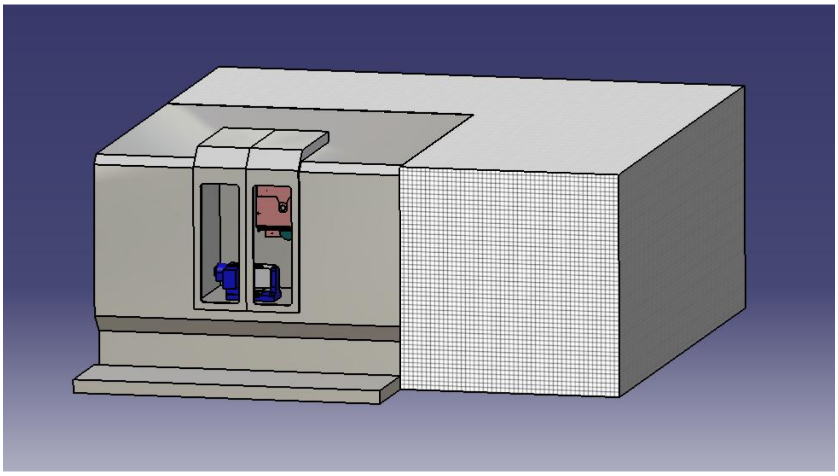
In order to allow for an easy positioning of the fixture on the workpiece support, the grinding tool block (represented in pink), is able to move up so that the space available to the robot for fixture dropping is larger, and collisions with the tool can be avoided. It's important to recall that, as a consequence of the specific configuration of the fixture and the robot gripper as well as the cone, the release of the fixture by the robot requires a horizontal movement towards the workpiece support and a following vertical movement to locate the fixture on the ISO cone. This movement requires a minimum height between the grinding tool and the workpiece support, that can be obtained by moving up the grinding tool. The grinding tool movement has been introduced in the model and simulated to verify the feasibility of the fixture release in realistic conditions. Fig. 9 a-b show the different positions of the grinding tool: (a) the tool is down for machining, (b) the tool is up to leave sufficient space for part placing on the workpiece support.

Fig. 7.43 a-b show the machine tool model in the open and closed position: it has been created as a device, that is a product with moving joints, in order to simulate door closing and opening as well as grinding tool moving up and down.

The subsequent image (Fig. 7.44) focuses in detail on the interaction between robot and machine, by showing the moment when the robot releases the fixture on the workpiece table.



(a)



(b)

Fig. 7.43. 3D model of the grinding machine without control block: (a) Open. (b) Closed.

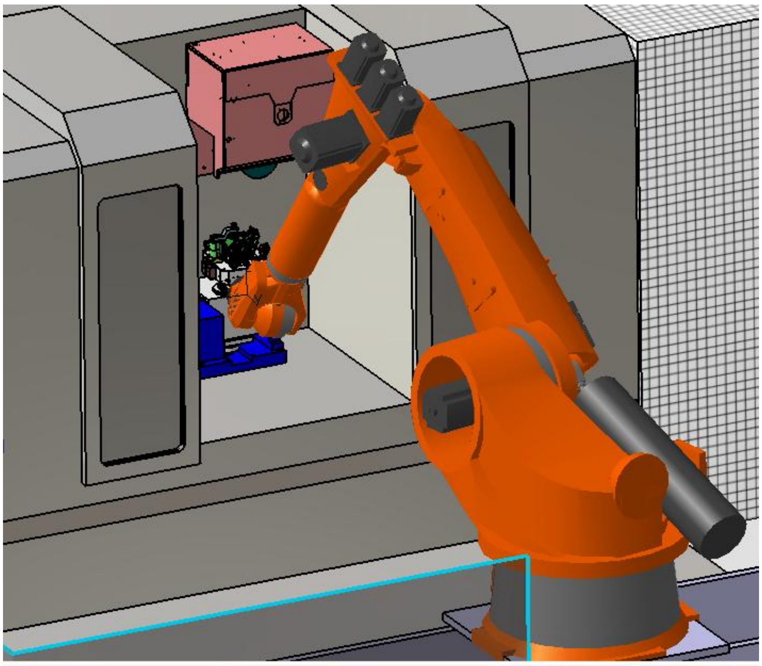


Fig. 7.44. The robot places the fixture on the grinding machine.

A further device to be considered is the machine control block, similar to the 3D model in Fig. 7.45. It was decided to remove the control unit from the front of the machine tools, since when the cell is completely automated, the human operator will have access to a remote control block located outside the cell and governing the two grinding machine tools. This solution is convenient for the movement of the robot, since it removes an obstacle from the path that should be considered to avoid collisions.

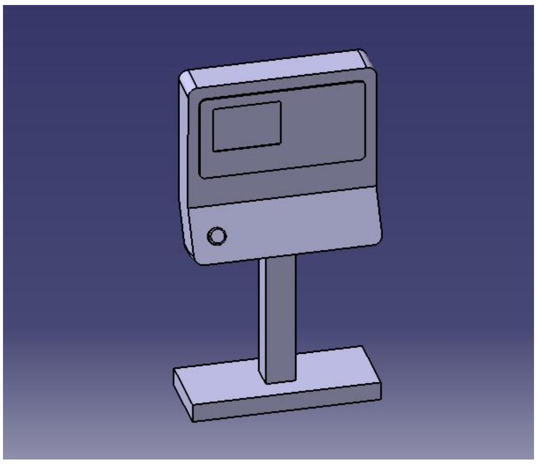


Fig. 7.45. The remote control block of the grinding machine.

COORDINATE MEASURING MACHINE

As regards the coordinate measuring machine present in the manufacturing cell, a DEA Global CMM, a 3D model of such machine has been obtained from DELMIA V5 database, since it is a very common model, and is shown in Fig. 7.46. The part will be placed on the CMM table together with the fixture on which it is mounted for the entire manufacturing cycle: this will allow for a precise and quick positioning of the part, without affecting the capability of the CMM to measure the reference points, that will be reachable by the measuring tip. The part mounted on the fixture, however, cannot be directly placed on the CMM table for two main reasons: the first is that the assembly should be stable and in a precise location in order to carry out measurements on it, the second is that the robot needs some space between the fixture and the table in order to avoid hitting on the table surface when placing the part mounted on the fixture (as shown in Fig. 7.47 a). A support is then needed on the CMM table: it can be provided with a cone similar to those used on the grinding machine, allowing a simple and precise positioning with a vertical movement. The robot placing the fixture on the CMM provided with a suitable support is shown in Fig 7.47 b.

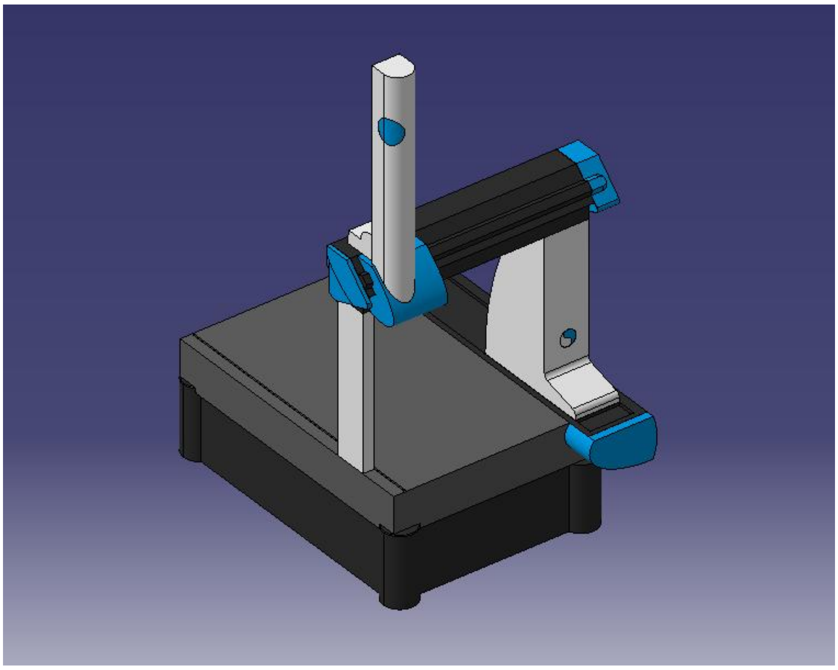
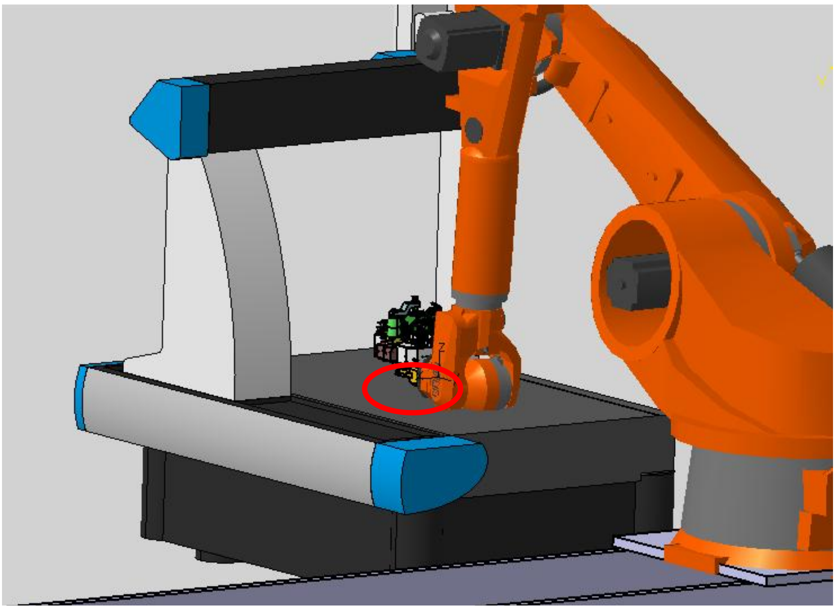
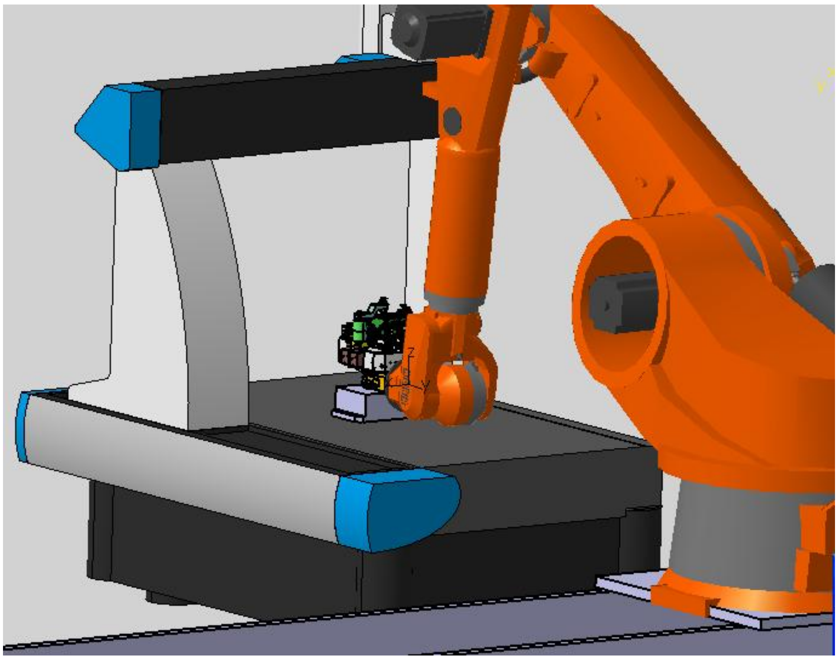


Fig. 7.46. 3D model of the DEA Global CMM.



(a)



(b)

Fig. 7.47. Robot placing the fixture on the CMM table: (a) Without support. (b) With support.

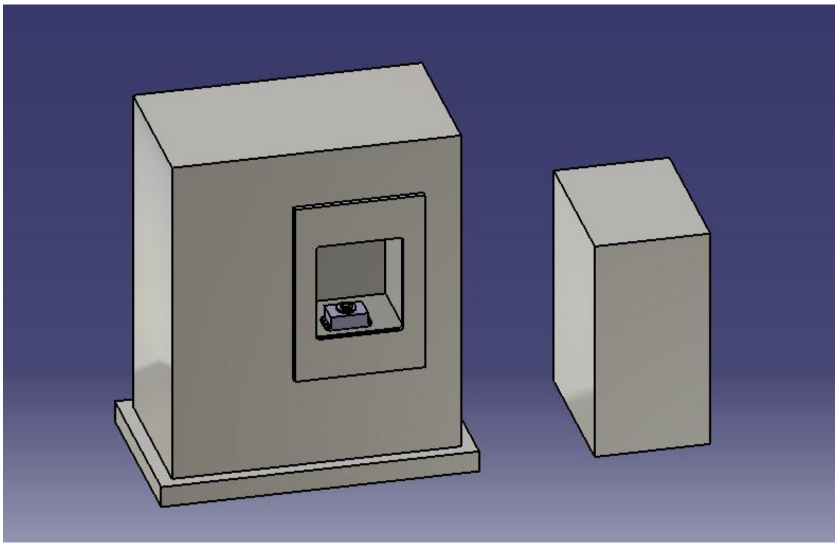
WASHING STATION

In the Avio facility of Acerra, a horizontal loading washing machine (AUTOCLEAN 50) is available, as shown in Fig. 7.48 together with its controller. This machine is an hermetic device which allows combined hot liquid and vapour phase degreasing. It is programmed for automatic degreasing operations and times for each step are defined by a suitable program.

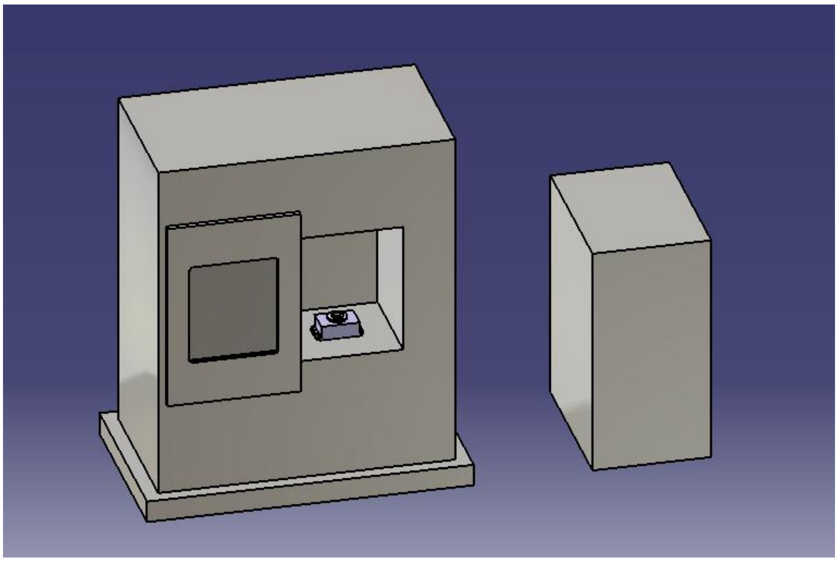
Fig. 7.48. Horizontal Loading Washing Machine.

The washing machine should be provided with an automatic door, capable to open when the robot comes to load a part mounted on the fixture.

3D models of the washing machine as well as its control block have been realised in order to introduce them in the global manufacturing cell model. It must be remarked that the main block of the washing station has been modelled as a device, provided with its own motion, in order to simulate the door opening/closing actions that will happen automatically in the manufacturing cell. Moreover, a specific support similar to those mounted on the CMM and the racks has been put inside the washing machine to allow for a precise positioning of the fixture and to avoid hitting of the robot hand on the machine. The 3D model of the washing station is shown in Fig. 7.49 a-b, both in the closed and open position.



(a)



(b)

Fig. 7.49. 3D blocks representing the washing station and controller: (a) Closed. (b) Open.

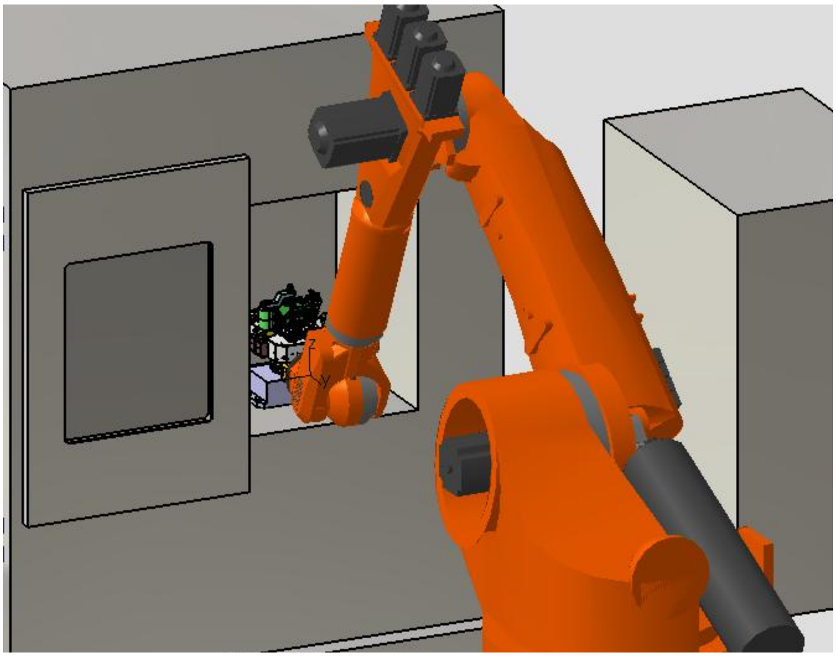


Fig. 7.50. Robot placing the part mounted on the fixture in the washing station.

DEBURRING STATION

Deburring is performed in order to remove chips and burrs on the grinded surface. Various deburring tools are employed, such as deburr mills, big abrasive stones, small abrasive stones, abrasive paper (size 400) and air compressor plug in devices.

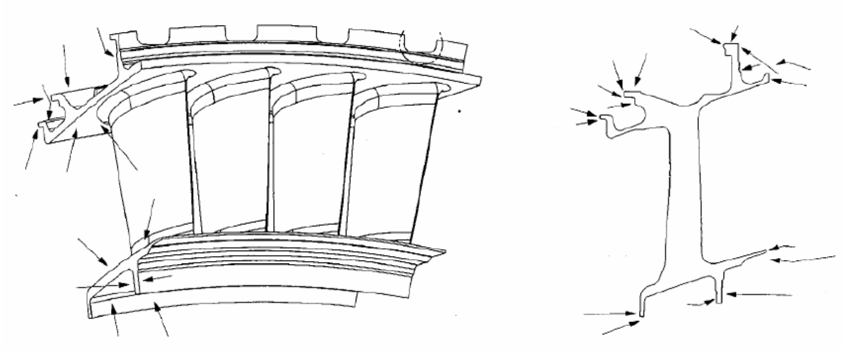


Fig. 7.51. Grinded surfaces where deburring must be performed.

The deburring station has been considered as a separate automatic device in the manufacturing cell, so that the robot will simply have to put the parts mounted on the fixtures at the entrance of this zone, and pick them at the exit.

The buffer at the entrance of the deburring station is represented as a rack similar to those currently available at Avio facility. Dimensioning of this buffer is not a main issue at this stage, since it should only have 2 positions, one for parts entering the deburring station, one for parts exiting. All the extra parts should be placed on the intermediate buffers located on the side of the manufacturing cell. On this rack, as on any other element of the cell, a support is needed to put fixtures on, as otherwise the robot would not be able to place them on the rack (see Fig. 7.53 a-b). The deburring place has been represented as an automatic station where a dedicated robot (smaller than the KUKA KR100P-2) takes the parts from the buffer and performs deburring on an apposite worktable.

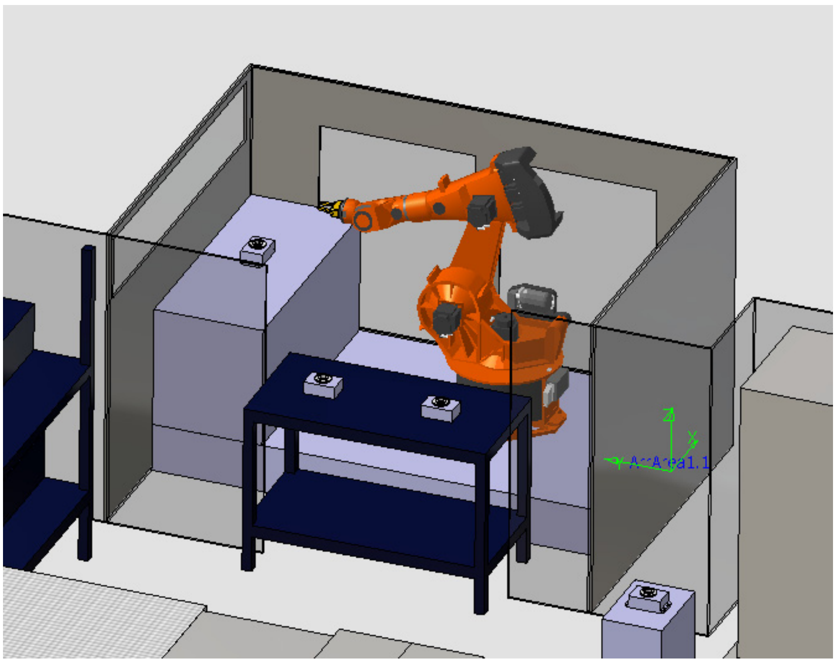
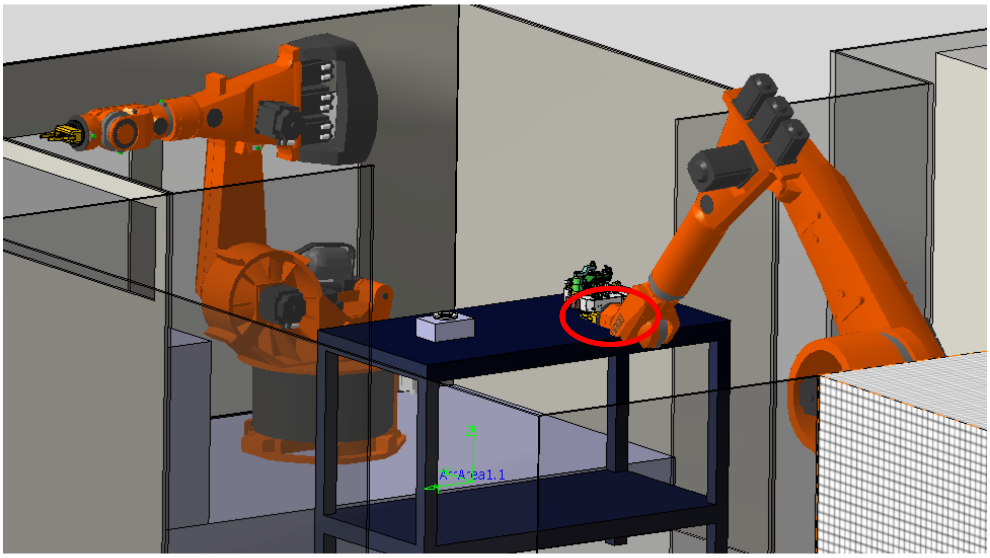
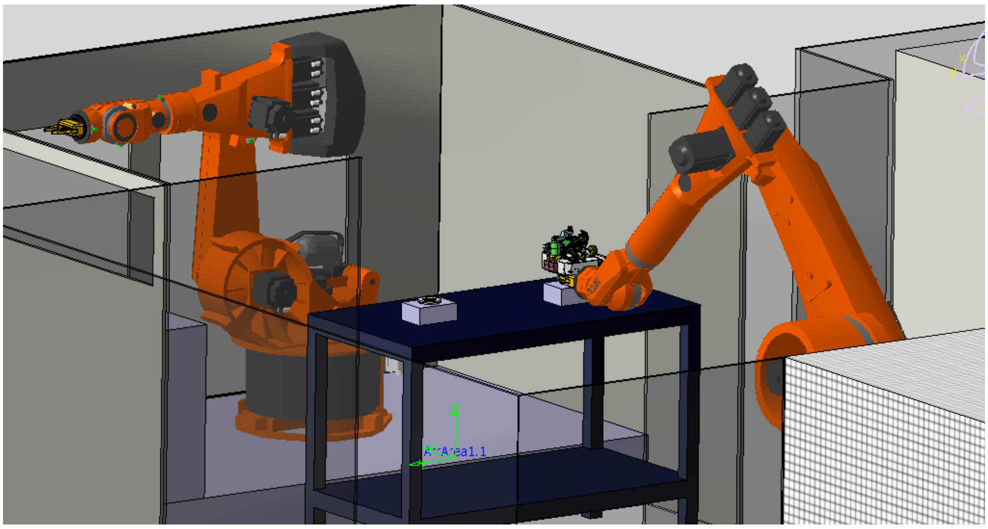


Fig. 7.52. Deburring station.



(a)



(b)

Fig. 7.53. Robot placing the fixture on the rack. (a) Without support. (b) With support.

ASSEMBLY WORKBENCH

The assembly station consists of a bench where the operator should mount the vanes on the apposite fixtures, and dismount them at the end of the manufacturing process. The fixtures can only be moved by the robot, because they are too heavy, and this implies that the robot must place the fixture on the table, and only after that operation the human operator can mount the part on it. In a first instance, the assembly station has been represented as a simple worktable. Further considerations, though, imposed to change such configuration. The manufacturing cell has been conceived as an automated area where the robot can safely move without the presence of human operators, because that could be dangerous for them. Most of the machines in the cell (grinding machine tools, washing device, racks,…) are only reachable by the robot, and they don't need human operation. The assembly workbench, on the contrary, represents a particular element because it is the place where both robot and human operator must work. Since it must be reachable by the robot, it should be inside the automated bounded area, but as it must also be reachable by the human operator, it should also be outside that area. The basic rule is that the place where the human operator acts should not be reachable by the robot, so a suitable solution is to create a moving surface that can enter and exit the bounded area becoming accessible to human and robot in different moments. The assembly workbench could then be modelled as a rotating table: the part is placed on the rotating platform of the table by the robot inside the cell, then the rotation of the platform carries the part outside the bounded area making it available to the human operator. After a research on the currently available industrial rotating table, a model produced by the German company Weiss has been chosen. The 3D model of that rotating table has been modelled as a device, capable to rotate its platform, and is shown in Fig. 7.54.

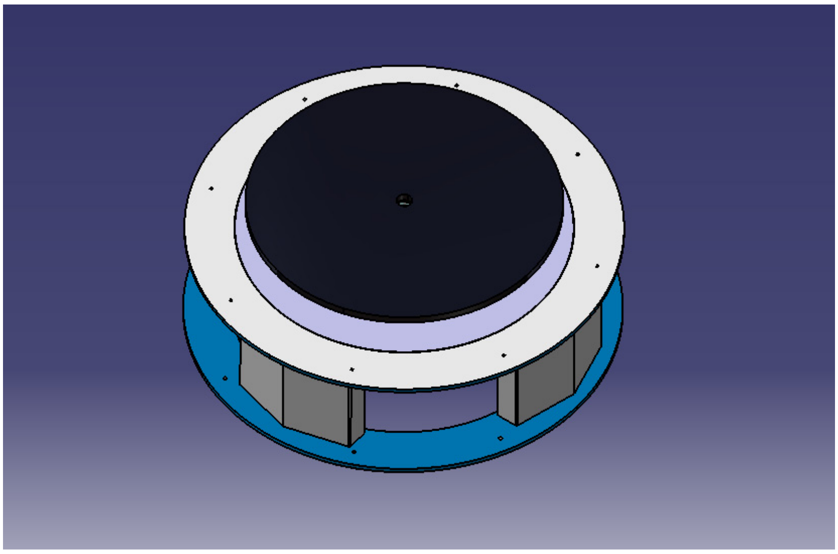
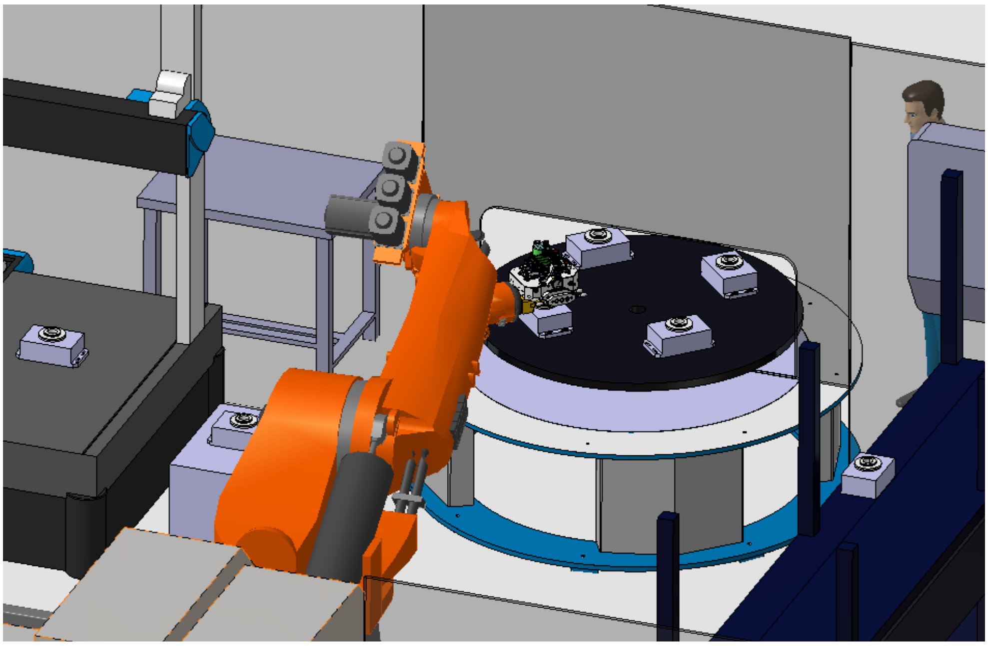
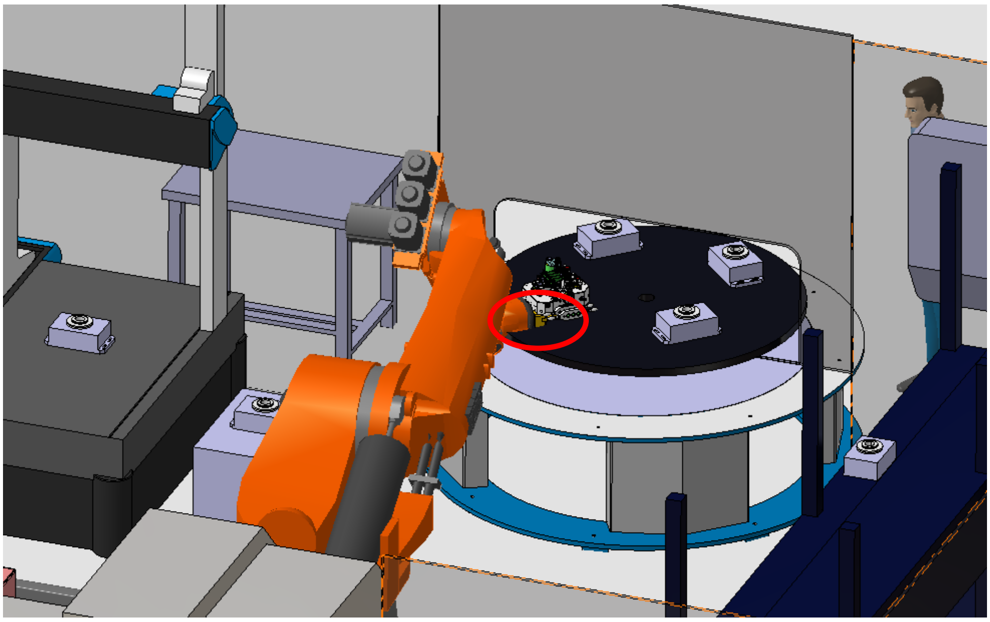


Fig. 7.54. Rotating table for the assembly station.

On this table, as on the other elements of the manufacturing cell, a support for the fixture must be placed both to allow a stable position of the fixture and to make the location reachable by the robot without hitting on the surface of the table. Fig. 7.55 a-b show the robot placing the fixture on the rotating table with and without the proper support.



(a)

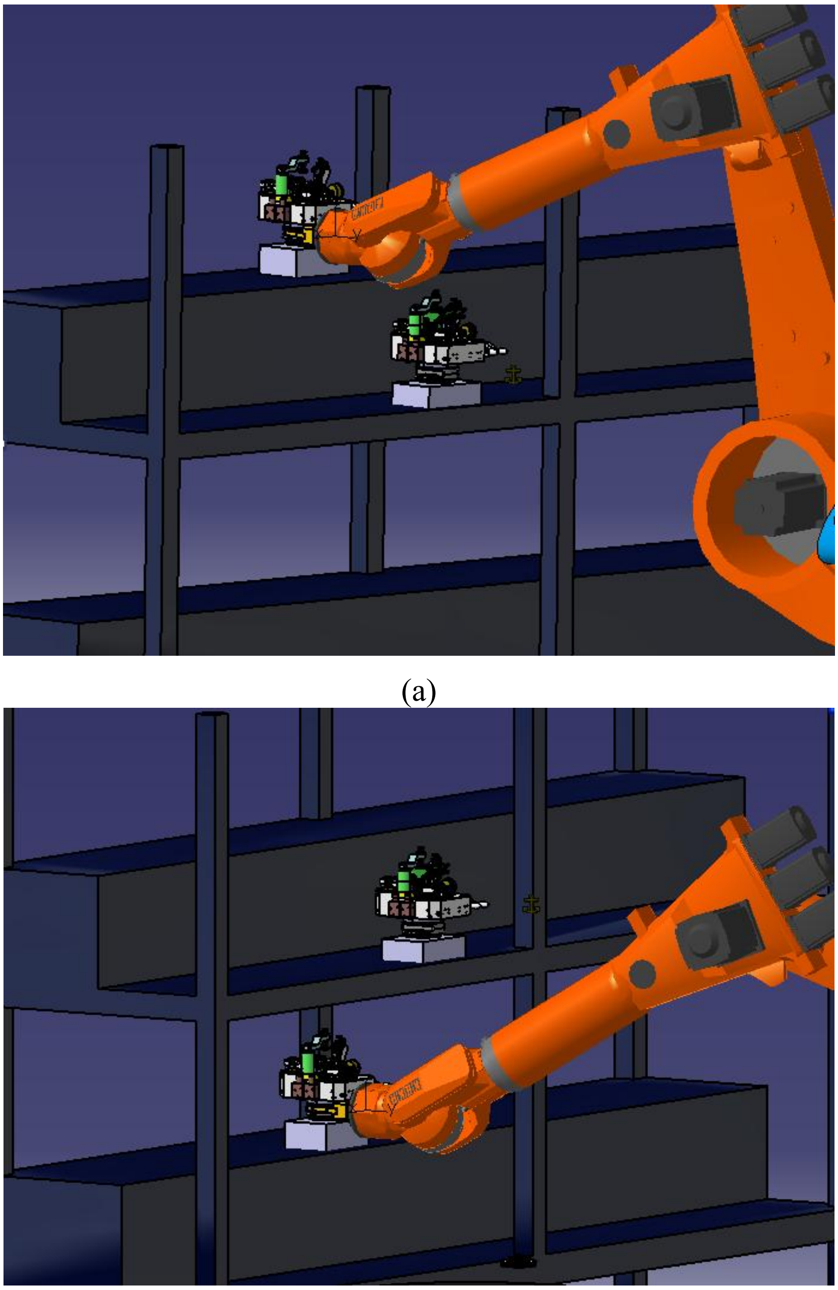


(b)

Fig. 7.55. Robot placing the fixture on the assembly table: (a) With support. (b) Without support.

BUFFERS

The manufacturing cell includes two large buffers: the first is dedicated to the collection of fixtures to be assembled to the vanes, the second is an intermediate buffer where vanes mounted on fixtures are stored while waiting for machines to become available. These buffers have been represented as racks similar to the one used at the entrance of the deburring station, as this model is already available at Avio facility. The problem in this case is that the capacity of these buffers must be higher that 2: this means that the racks should be larger and in order to save space the fixtures should be placed on two rows on each shelf. Since the type of support for the fixtures and the gripper mounted on the robot require the fixture to be accessible both horizontally and vertically, the second row of each shelf should be higher (at least 400 mm) than the first one. A solution to this problem could a small change in the rack configuration, consisting in the creation of shelves provided with two levels. Fig. 7.56 a-b shows the robot placing the fixture on the shelves.



(a)

(b)

Fig. 7.56. Robot placing the fixture on: (a) Higher shelf. (b) Lower shelf.

7.6.2 MANUFACTURING CELL 3D SIMULATION

On the basis of the starting scheme of the manufacturing cell shown in Figure 1, all the components of the cell were arranged to set up the global layout with properly dimensioned machines and devices. For layout optimization, though, further analysis is necessary. In particular, much attention must be paid to safety, in order to avoid any type of interference between the robot movement and the other equipments of the cell as well as the labor movements. Moreover, to determine the appropriate arrangement for the components of the manufacturing cell and their relative distance, the constraints related to the robot accessibility should be taken into consideration. In this perspective, the employment of 3D simulation proves essential to allow for virtually verifying the activities that the robot has to carry out in the manufacturing cell, and for determining if the current arrangement permits to perform all the activities, both in terms of reachability and safety against possible collisions.
In order to examine these aspects, robot activities were created using the Robot Task simulation application available in DELMIA V5. Tasks were created by placing tags on all the objectives that the robot should reach in manufacturing cell, as shown in Fig.7.57.

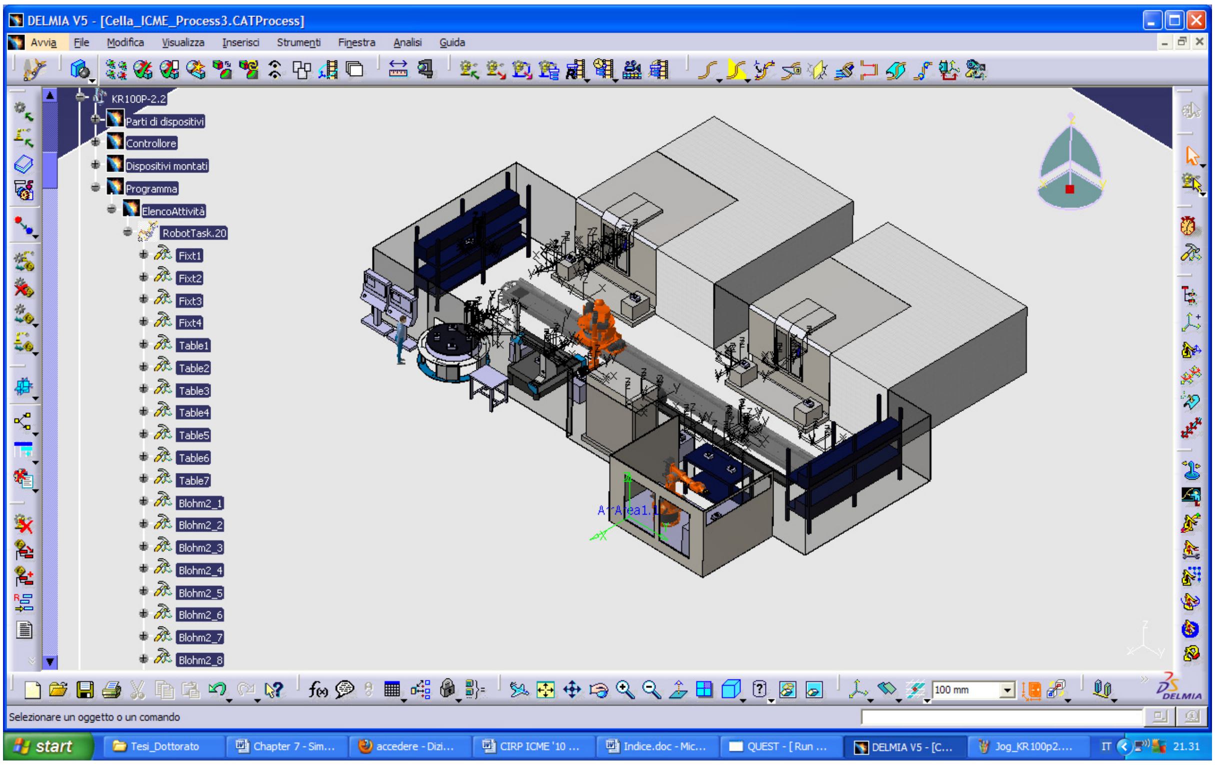


Fig. 7.57. Robot tasks in the DELMIA V5 model.

The first problem to be examined was the length of the robot rail. By arranging all the machines on the working area, and keeping at least a minimum distance (maintenance distance is 500 mm) among them, the dimensioning of the robot rail was carried out. The length of the KL1500-2 rail can vary on the basis of the required application and is equal to 1840 mm + nominal travel (minimum travel, 1000 mm, maximum travel, 30000 mm, travel graduation, 500 mm). In this case, it was set equal to 13350 mm, since the simulation of the robot tasks allowed to verify that this dimension is sufficient to cover the area of the manufacturing cell that should be reached by the robot.

Another purpose of this simulation is to determine the proper distance among the robot rail and the surrounding machines. This distance depends on the robot dimensions and is constrained by the necessity to reach all the targets for part placing. By creating tags (target points) in the 3D simulation software, it was possible to check if the robot is able to reach all the targets with the current layout, and modify the configuration if this condition is not verified. Since the robot chosen for this manufacturing cell has a very wide action range, it is able to reach points that are quite far from the rail. On the other hand, points that are too close cannot be reached because of the constraints on the robot joints, so that a minimum distance between the machines and the rail is imposed.

The characterization of the minimum distance of the machines composing the manufacturing cell was performed through simulation of robot tasks. As regards the location of the grinding machine tools, a suitable distance of the machine platform was found to be 1500 mm from the robot rail, while for the washing machine it is 1800 mm. At this distance, the simulation showed that the robot can easily move towards and outwards the machines, and all the required positions are reachable. If the machines were closer to the rail, the robot could not reach the target inside the machine and exit without hitting on the sides of the machine. Figure 7.59 a-b shows the two simulation cases where the washing machine is too close to the robot rail and where it is properly distanced.

In order to deal with operation safety in the manufacturing cell, not only collisions between robot and machines should be taken into account, but also troubles related to human-robot interaction due to the presence of a human operator mounting and dismounting vanes and fixtures on the assembly table.

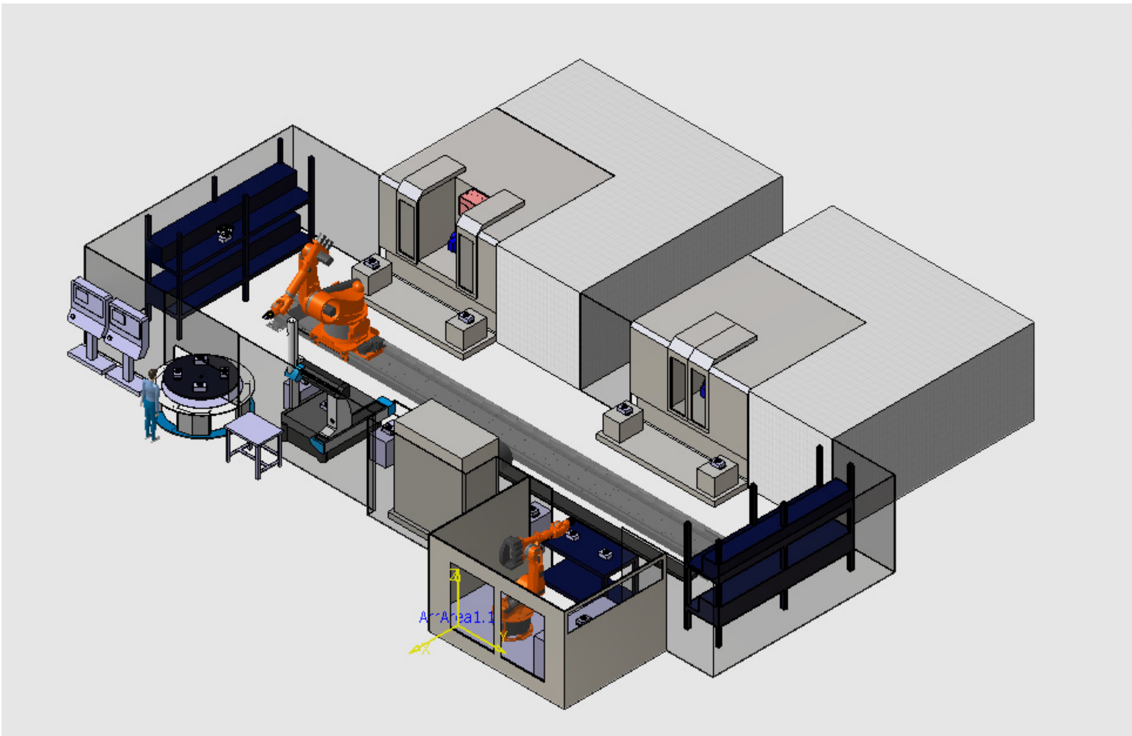
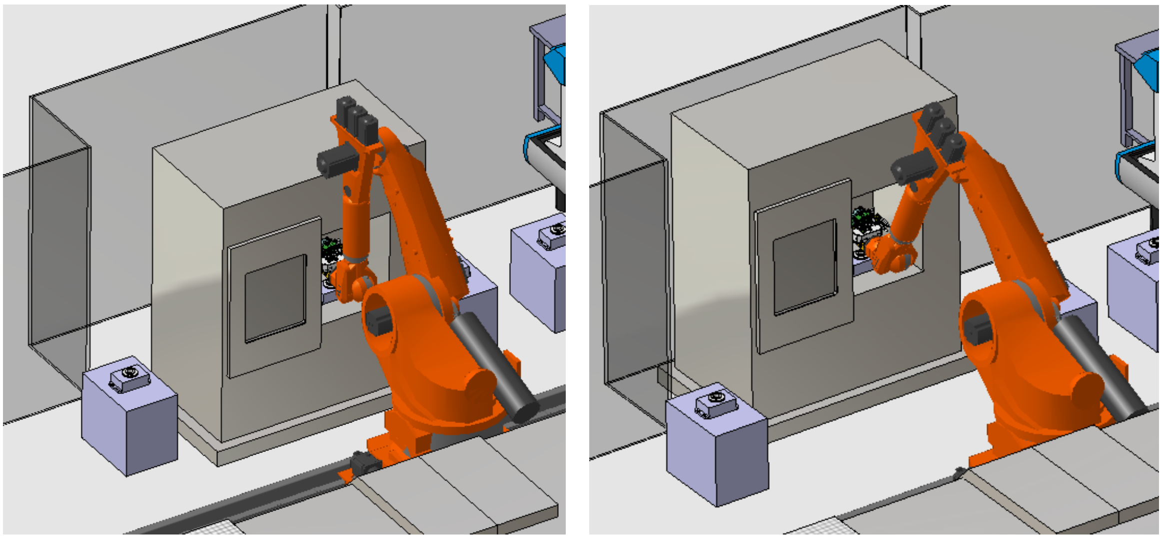


Fig. 7.58. 3D model of the manufacturing cell for 3D motion simulation.



(a) (b)

Fig. 7.59. Washing machine (a) too close to the robot. (b) properly distanced.

A possible solution consists in closing with a barrier the entire zone of the manufacturing cell where the robot should move. The simulation helps identify the zones where communication with the external environment should be allowed.

In particular, the mounting table was configured as a rotating table provided with input and output positions: once the labor has mounted the part on the fixture outside the cell, the part enters the bounded zone automatically.

The rotating table allows the operator to use a working position distinct from the area where the robot works. A slot was designed in the barrier with a height sufficient to allow the transfer of the part mounted on the fixture.

Another element that should communicate with the area outside the manufacturing cell is the deburring station. The robot puts the parts mounted on fixtures on a rack, and an automatic device will draw them. This means that the rack should be reachable both from inside and outside of the MC: for this reason, the barrier bounding the manufacturing cell is interrupted.

All the stations that don't require to be reached by the labor were located inside the boundaries of the MC. As regards the grinding machine tools, the robot should be able to place part and fixture inside them, while the labor needs to access the tool storage area located on the side for tool change and maintenance. For this reason, the safety barrier was placed in line with the front of the machine tool.

With the described layout configuration, shown in Figure 3, the simulation of robot movement throughout the cell was carried out to investigate the feasibility of the entire manufacturing cycle. A cycle was simulated to verify the possibility of the robot to reach each single target, as well as to examine the path followed by the robot from one target to another, and check if any collision occurred during motion.

The simulation involved the following steps:

– the robot reaches the fixtures buffer and draws fixture 1
– the robot places fixture 1 on the assembly table
– the assembly table rotates
– the labor reaches the table to mount a part on fixture 1
– the assembly table rotates
– the robot lifts part and fixture from the assembly table

- the robot goes to the CMM and releases part and fixture
- the robot draws part and fixture from the CMM
- the robot carries part and fixture to grinding machine 1
- the machine tool doors close, grinding is performed, machine tool doors open
- the robot lifts part and fixture from the machine
- the robot places part and fixture on the assembly table
- the assembly table rotates to transfer the fixture outside
- the labor reaches the table to dismount part and fixture
- the robot reaches the fixtures buffer and draws fixture 2
- the robot places fixture 2 on the assembly table
- the assembly table rotates
- the labor reaches the table to mount a part on fixture 2
- the assembly table rotates
- the robot lifts part and fixture from the assembly table
- the robot carries part and fixture to grinding machine 2
- the machine tool doors close, grinding is performed, machine tool doors open
- the robot lifts part and fixture from the machine
- the robot moves part and fixture to the deburring station rack
- the automatic deburring device draws part and fixture
- deburring is performed
- the automatic deburring device places part and fixture on the deburring station rack
- the robot draws part and fixture from the deburring rack
- the robot moves part and fixture to the washing station
- the washing station door closes, washing is carried out, the door opens
- the robot draws part and fixture from the washing station
- the robot moves to the CMM and places part and fixture
- the robot draws part and fixture from the CMM
- the robot places part and fixture on the assembly table
- the assembly table rotates to transfer the fixture outside
- the labor reaches the table to dismount part and fixture

The 3D simulation allowed to identify a suitable layout for the manufacturing cell, allowing the robot to reach all the targets. Moreover, it represented a useful instrument to analyse the movements that the robot should make to perform its tasks, in particular for part loading/unloading on machines and racks. As regards cycle times related to the robot tasks, they can be easily observed through the Gantt chart generated by the 3D simulation software, as shown in Fig. 7.60. The normal Gantt chart is activity-centric and allows for overall cycle-time analysis for a set of activities The Gantt chart visualization is based on either the specified or calculated cycle times defined for each activity.

7.7 CONSIDERATIONS ON THE INTEGRATION OF DES AND 3D SIMULATION

The 3D simulation results offered new valuable information to enhance the DES of the reconfigured manufacturing cell. This is consistent with the Digital Factory approach, where integration of data from different tools has a fundamental role, since a single simulation tool cannot take into account all the relevant issues for a comprehensive planning process. A correspondence between the data generated within the 3D simulation software DELMIA V5 and the data that can be usefully employed to enhance the DES model built in QUEST can be represented as reported in Table 7.12.

3D simulation data	Correspondent DES simulation data
3D CAD Models	**3D Models in QUEST format**
Robot Activities Cycle Times	**Robot Loading/Unloading Times**
Robot Rail Speed	**Robot Travel Speed**
Layout Arrangement	**Layout Arrangement**

Table 7.12. Correspondence between 3D simulation and DES data.

Taking into consideration the arrangement of the manufacturing cell elements resulted from the 3D simulation, the layout of the DES model was modified.

Since 3D models of the manufacturing cell elements with their actual geometry had been already built within the 3D simulation software, they could be imported in the DES software using the standard exchange format IGES, as shown in Fig. 7.60. The model already built in the DES software for the initial simulation could still be employed since model logics are not affected by changes in elements display and arrangement.

In order to be able to update 3D models of the manufacturing system elements, a common database containing all the 3D files should be created, for example by using a common exchange format such as IGES, in order to allow compatibility with different software tools.

Other relevant data for the enhancement of the DES model are represented by the robot travel speed and the loading/unloading time on machines. In the previous model, they were estimated on the basis of generic values for industrial robots, without reference to a specific robot model, so that the DES model needs to be refined. More detailed data were provided by the 3D simulation. In fact, a correspondence between the robot rail speed in DELMIA V5 and the robot travel speed in QUEST can be found. Moreover, the analysis of the robot activities carried out in DELMIA V5 allows to calculate cycle times required for loading and unloading operations performed by the robot. So, the illustrated simulation data were exported from DELMIA V5 and introduced in QUEST, in order to update the manufacturing cell model with refined data.

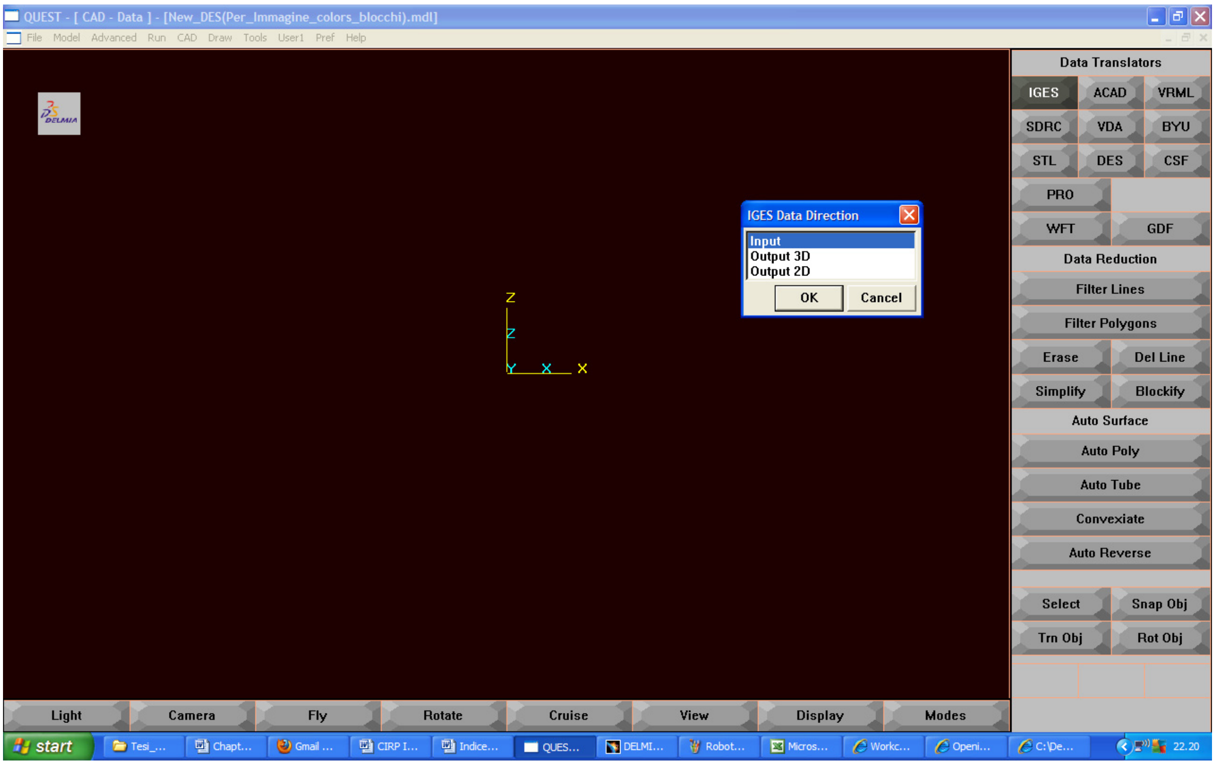


Fig. 7.60. IGES file import in QUEST.

7.8 Enhanced DES of the Robotic Manufacturing Cell

Taking into consideration the layout of the manufacturing cell elements resulted from the 3D simulation, the layout of the DES model was modified by setting the same arrangement and the same distance among the elements, obtaining the layout shown in Fig. 7.61.

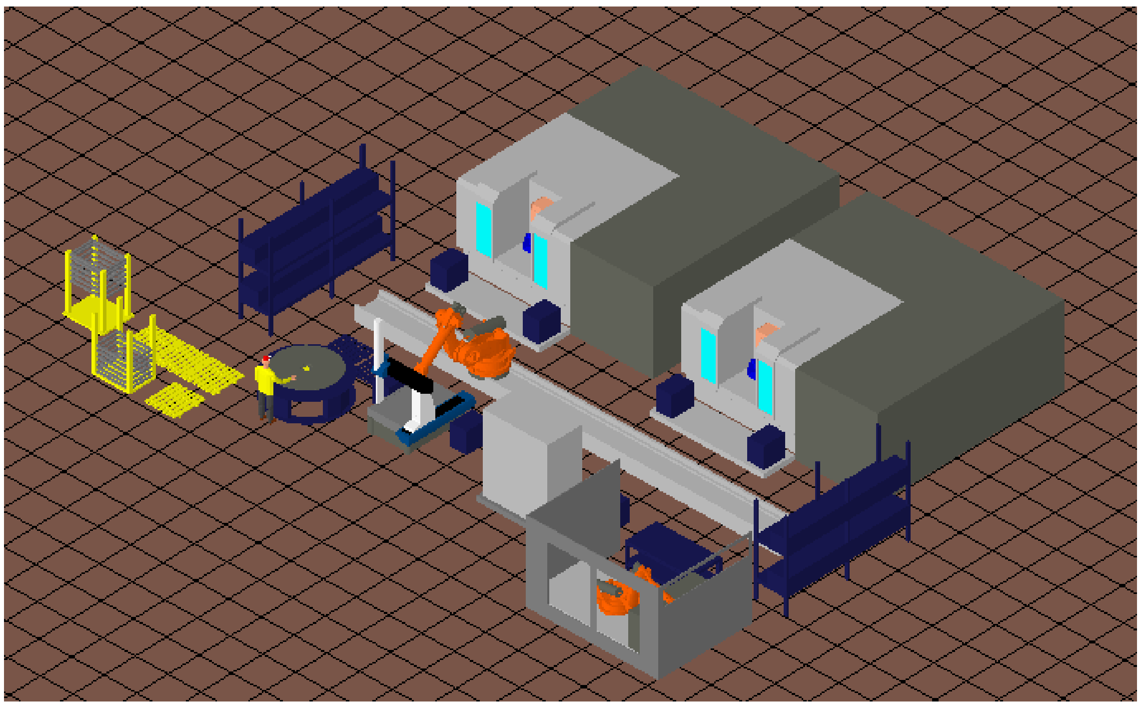


Fig. 7.61. 3D model of the manufacturing cell for DES within DELMIA QUEST.

Moreover, travel speed was set on the basis of the KUKA KL1500-2 rail speed, while loading/unloading times of the robot on the manufacturing cell elements were taken from the 3D simulation cycle times.

The updated DES model was then simulated in QUEST to better evaluate the effects of the introduced modifications of the manufacturing cell with reference to productivity and utilization of the available resources. As suggested by the previous work on DES, the number of fixtures was increased to 2 for each type. In this way, the presence of the assembly workbench can be fully exploited, since mounting and dismounting operations can be carried out by the labor in parallel with machining processes performed on the grinding machines. The data generated by this simulation showed that the total time required to produce an entire kit of vanes was 2884 min (6.01 work shifts). If compared to the total production time of the existing manufacturing cell, 3940 min, it provides a decrease of 27%.

Below, the utilization of the manufacturing cell machines is shown in Table 7.13 in numerical form, and in the Fig. 7.62-7.71 in form of charts.

Element	Utilization (%)
Machine 1	97
Machine 2	65
CMM	45
Deburring	15
Washing	7
Mounting Table	37

Table 7.13. Utilization of the manufacturing cell machines.

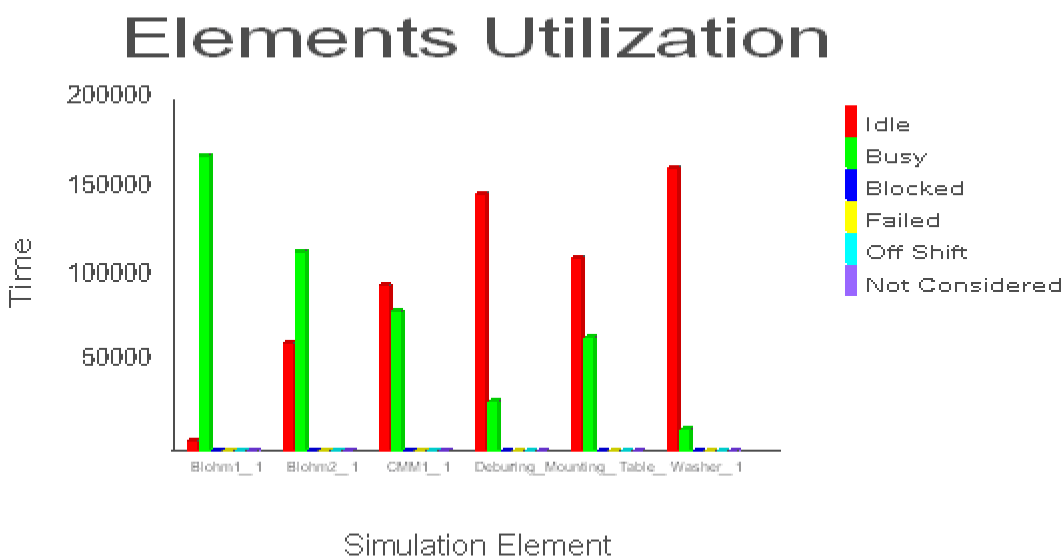


Fig. 7.62. Utilization of the manufacturing cell machines.

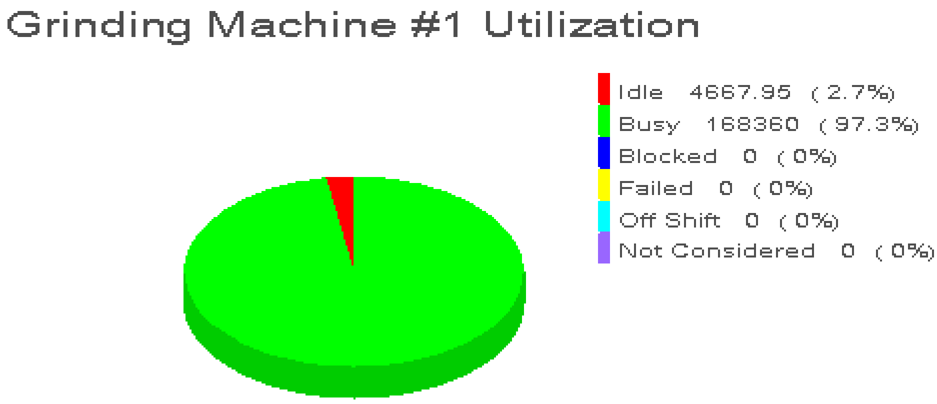


Fig. 7.63. Grinding Machine #1 Utilization

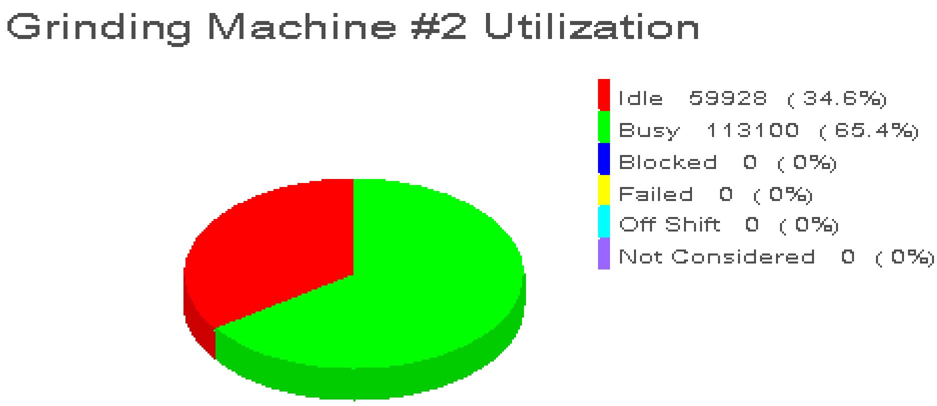


Fig. 7.64. Grinding Machine #2 Utilization.

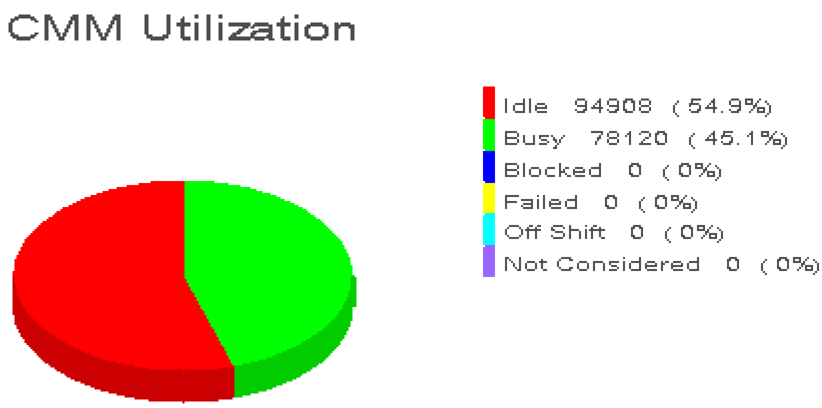


Fig. 7.65. CMM Utilization.

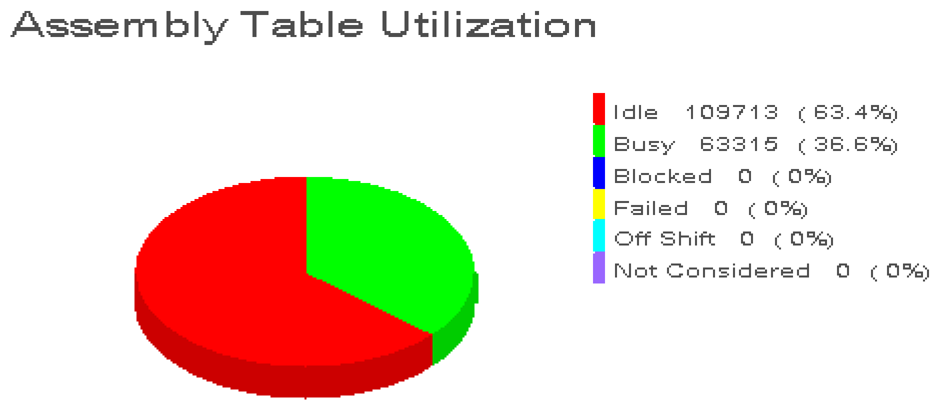


Fig. 7.66. Assembly Table Utilization.

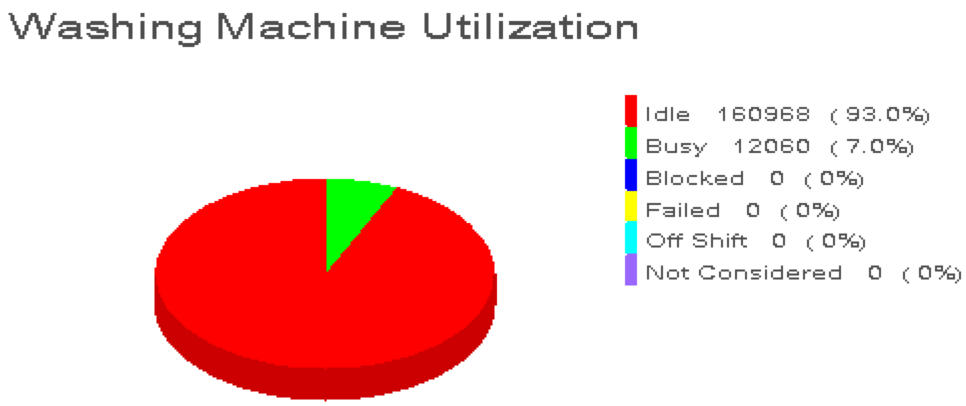


Fig. 7.67. Washing Machine Utilization.

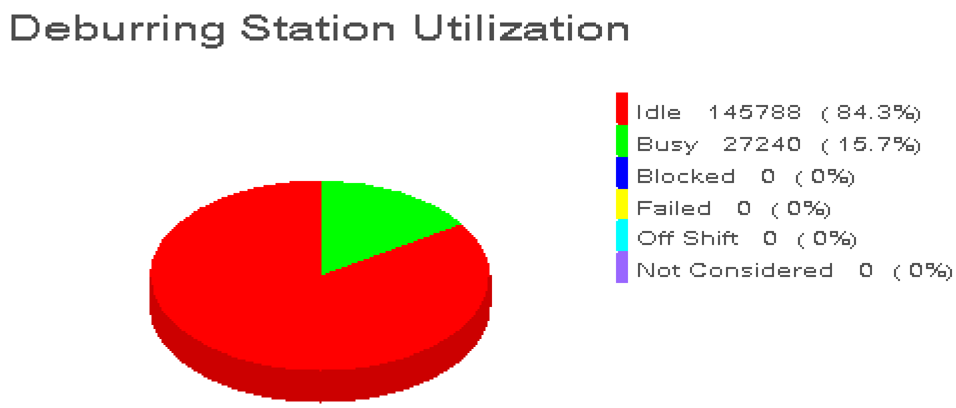


Fig. 7.68. Deburring Station Utilization.

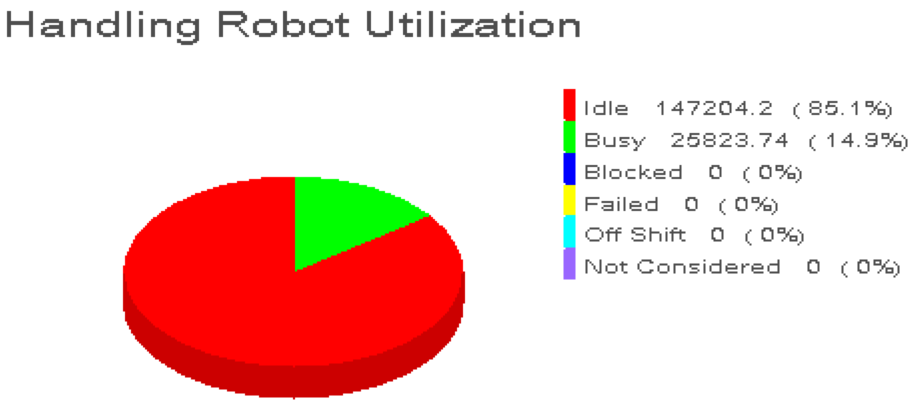


Fig. 7.69. Handling Robot Utilization.

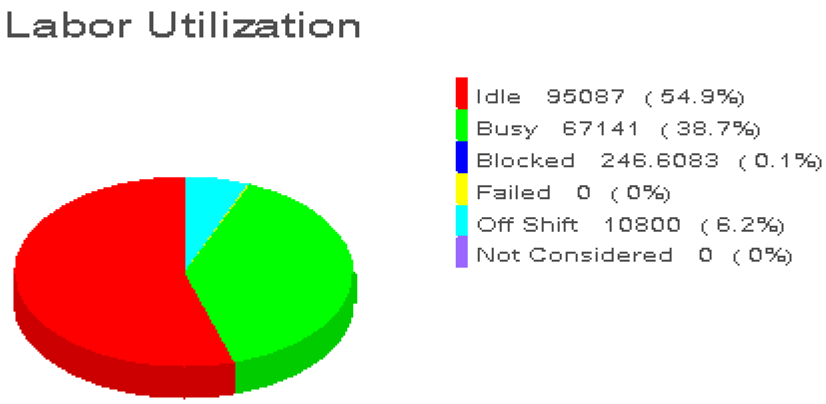


Fig. 7.70. Labor Utilization.

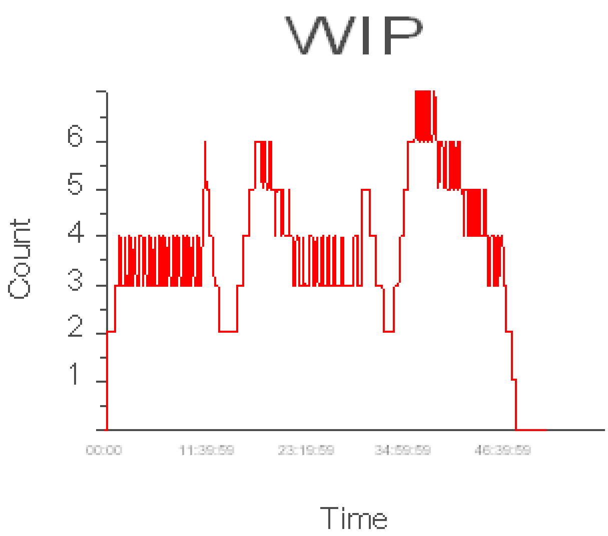


Fig. 7.71. Elements contemporarily in the system.

7.9 SUMMARY

Two different categories of simulation software tools were applied to the study of a real manufacturing cell dedicated to the production of turbine vanes in a real industrial plant of the Avio SpA company. The Discrete Event Simulation software QUEST was employed in order to analyse the actual system's behaviour in terms of production flow, productivity, utilization of the available facilities, bottlenecks of the system, and throughput time. Analysis of the simulation results was carried out to suggest possible areas of improvement that could increase efficiency and productivity, and a reconfiguration of the manufacturing cell through integration of a robotic material handling system was proposed.

The proposed modifications in the manufacturing cell were first simulated through DES to analyze the behaviour of the system. In order to perform a comprehensive analysis taking into consideration aspects related to robot motion, as the possibility to reach all the objectives, the safety of movements throughout the manufacturing cell and the configuration of a suitable layout, the 3D simulation software DELMIA V5 was additionally employed to perform a detailed design phase of the manufacturing cell.

The results of this 3D simulation concern layout modifications and the estimated robot loading/unloading and displacement times: this information is necessary in order to update and refine the manufacturing cell DES model and carry out a more reliable simulation of the virtual cell. For this reason, 3D simulation generated data were integrated within the DES software, where the behaviour of the manufacturing cell could be finally analysed with reference to productivity and utilization of the available resources. The refined DES model was then simulated and the results of the new simulation could be examined in order to make a comparison with the original manufacturing cell model, with the aim to support the decision making process.

The 3D simulation carried out on the manufacturing cell generated valuable results concerning the most suitable layout and the time required for robot movements throughout the cell. This information extracted from the 3D simulation allowed to enhance the DES model accuracy and significance of simulation analysis.

In most cases, a single simulation tool is not sufficient to perform a comprehensive analysis of a manufacturing system, and cannot take into account all the relevant issues in the planning or reconfiguration process. The advantages offered by the integration of the two simulation results are consistent with the main idea of the Digital Factory concept, that is based on the integration and data exchange among different tools for design, engineering, planning, simulation, communication, and control.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

8.1 SUMMARY

In this research, the main features of modern manufacturing were presented with particular emphasis on the turbulence and strong competition that characterise current global manufacturing environment. The most important manufacturing paradigms of the last century were illustrated, showing how the focus has been progressively moved towards systems flexibility and reconfigurability, in order to adapt to the uncertain external environment. It was shown how the indispensable requirements for modern reconfigurable (and flexible) manufacturing systems are related to system responsiveness, that enables:

- the launch of new product models to be undertaken very quickly;
- rapid adjustment of the manufacturing system capacity to market demands;
- rapid integration of new functions and process technologies into existing systems;
- easy adaptation to variable quantities of products.

The manufacturing systems conceived according to this new approach must be rapidly designed, able to convert quickly to the production of new models, to adjust capacity and functionality, and to integrate new technology in order to produce an increased variety of products in changeable quantities.

For that reason, the development of methods for rapid product and process realization is currently one of the major elements of competitiveness for the manufacturing industry. New technologies and innovations for future demands and development of the factory structures should be taken into account.

In order to meet all these requisites, efforts are currently spent to further introduce the role of information technology (IT) in modern manufacturing systems. Application of information technology in various stages of product design, production scheduling and process planning, machines control and processes monitoring (both on and off line), automation, quality control and networking and communication, and are now under deep study and are going through a rapid development.

On of the main areas of research is the development and implementation of integrated tools for manufacturing engineering taking into account the reconfigurability of systems, towards the realization of one of the most important technologies of the future: the Digital Factory.

The objective of the new Digital Factory concept is derived from this simple fact: the quality and fastness of changes can be supported by 3D digital models of production systems and a systematic and multi-scale data base.

According to this new concept, production data management systems and simulation technologies are jointly used for optimizing manufacturing before starting the production and supporting the ramp-up phases. Digital factory implementation would allow for, first, the shortening of planning time and cost, through the use of standard libraries, data integration and automation, second, the improvement of planning results quality, through systematic digital testing, third, the integration of knowledge coming from different manufacturing processes and departments, through integrated workflows, the ability to test alternatives and the visualisation of planning results (Chryssolouris et al., 2009; Haller et al. 2005).

The research activity developed in this thesis concerned the role of simulation in the Digital Factory approach, and the importance of data integration among different tools.

Two different categories of simulation software tools were applied to the study of a real manufacturing cell dedicated to the production of turbine vanes in a real industrial plant of the Avio SpA company. The Discrete Event Simulation software QUEST was employed in order to analyse the actual system's behaviour in terms of production flow, productivity, utilization of the available facilities, bottlenecks of the system, and throughput time. Analysis of the simulation results was carried out to suggest possible areas of improvement that could increase efficiency and productivity, and a reconfiguration of the manufacturing cell through integration of a robotic material handling system was proposed.

The proposed modifications in the manufacturing cell were first simulated through DES to analyze the behaviour of the system. In order to perform a comprehensive analysis taking into account aspects related to robot motion, as the possibility to reach all the objectives, safety of movements throughout the manufacturing cell and the configuration of a suitable layout, the 3D simulation software DELMIA V5 was additionally employed to perform a detailed design phase of the manufacturing cell.

The results of this 3D simulation concerning layout modifications and the estimated robot loading/unloading and displacement times was necessary in order to update and refine the manufacturing cell DES model and carry out a more reliable simulation of the virtual cell. For this reason, 3D simulation generated data were integrated within the DES software, where the behaviour of the manufacturing cell could be finally analysed with reference to productivity and utilization of the available resources. The refined DES model was then simulated and the results of the new simulation could be examined in order to make a comparison with the original manufacturing cell model, with the aim to support the decision making process.

In most cases, a single simulation tool is not sufficient to perform a comprehensive analysis of a manufacturing system, and cannot take into account all the relevant issues in the planning or reconfiguration process. The advantages offered by the integration of the two simulations are consistent with the main idea of the Digital Factory concept, that is based on the integration and data exchange among different tools for design, engineering, planning, simulation, communication, and control.

The realisation of the digital factory concept needs various software components such as design and planning software or simulation tools. All these have to function closely together. A single software system cannot cover the complete range of required functionalities: this can be achieved with the use of specialised software systems and their integration.

8.2 FUTURE DEVELOPMENTS

The implementation of the Digital Factory approach requires further research efforts to be fully realised. Many efforts are currently spent in order to solve problems related to data consistency inside the Digital Factory, related to the heterogeneity of tools and methods, in particular between the different simulations. Today there are no open, standardised, and universally accepted data sharing or intermediate formats capable of covering the whole chain. Up to now, several proposals have been presented in recent research studies, concerning the employment of XML language, application protocols or the definition of proper ontologies. Future research work will certainly focus on open standard interfaces available for integration of various software tools into the digital factory system architecture. New solutions will be certainly envisaged since a rapid development of information technology (IT) continuously offers new tools.

A further challenge is related to models management in the Digital Factory: appropriate building blocks and modelling elements as well as standard operation strategies should be made available in libraries. Hierarchical modelling is a future trend for analysis of complex systems, as it supports decomposition of models and distributed analysis of submodels in teams. Moreover, the complexity of models should be made scalable, not only through hierarchical modelling, but providing the possibility to switch on and off elements that are not necessary for the current simulation. Different models contain various levels of information: the next step could be to define the various multi-layered models for the different simulation tools used in the Digital Factory and to create links between all the structural layers. This would help focusing attention on the aspect relevant for the specific analysis objective.

Finally, the introduction of new technologies such as Reverse Engineering could be increasingly exploited in the future. As an example, let's consider the system for the design of shop floor 3D layouts and creation of 3D models of production halls. In current Digital Factory solutions, it is possible to create the 3D model of a production hall directly in CAD systems. Such solution is advantageous for new layouts or new production systems designs. However, when production halls already exist, as in most of real cases, it can be more effective to create 3D models of production halls with the employment of reverse engineering technologies, for example based on 3D laser scanning. This would allow to avoid all the manual measurements required before starting to design.

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