INSTITUTO TECNOLÓGICO Y DE ESTUDIOS SUPERIORES DE MONTERREY

Campus Monterrey

Escuela de Ingeniería y Tecnologías de Información

Programa de Graduados

EVALUATION, OPTIMIZATION AND SIMULATION OF THE PRODUCTION OF A TESLA TURBINE AND STIRLING MOTOR IN A RECONFIGURABLE MANUFACTURING SYSTEM

TESIS

PRESENTADA COMO REQUISITO PARCIAL PARA OBTENER EL GRADO ACADEMICO DE:

MAESTRÍA EN CIENCIAS CON ESPECIALIDAD EN AUTOMATIZACIÓN

POR:

LUIS FERNANDO RIVERO PÉREZ

MONTERREY, N.L. DICIEMBRE 2012

Dedicatoria

A Dios, por haberme dado la oportunidad de seguir creciendo profesionalmente y haberme dado las fuerzas, la sabiduría y la inteligencia para desarrollar esta tesis.

A mis Padres, por el sacrificio que hicieron de permitirme estudiar en esta prestigiosa universidad y por su apoyo incondicional en todas las áreas de mi vida en esta etapa.

Agradecimientos

A **CONACYT** por el apoyo y sustento económico brindado durante toda la maestría

Al **M.C Ricardo Jiménez**, por darme la oportunidad de trabajar en su equipo, guiarme durante el desarrollo de este trabajo y sobre todo por su apoyo para poder adquirir el conocimiento necesario para el desarrollo de la misma.

Al **Dr. Federico Guedea, Dr. Jorge A. Cortés y Dr. Eduardo Cárdenas** por sus comentarios y retroalimentaciones a este trabajo de tesis, que fueron de un enorme valor para el perfeccionamiento de la misma.

SUMMARY

Emerging economies and new ways of doing business are changing the world in a dramatic manner, these changes suggest that new competitive advantages must be created within companies to be able to develop customized products and cost effective manufacturing systems.

Reconfigurability has been an issue in computing and robotics for many years. In general, reconfigurability is the ability to repeatedly change and rearrange the components of a system in a cost-effective way. In this thesis two products are manufactured in a Reconfigurable Manufacturing System (RMS) that has the ability to rearrange the conveyor belts because these were manufactured as modules.

This research shows the evaluation and improvement of production process of a Tesla Turbine and the creation of the production process of a Stirling motor in a Reconfigurable manufacturing system. Also the two production processes were simulated in “Plant Simulation”. The methodology used to reach the objectives is based in the development of three main stages. The first stage “Obtaining of operations times” has the purpose of get the times of each operation involved in the production process. The second stage “Definition of the Process Flow” has the purpose of define the number of pallets, their contents and their flows in the Manufacturing Cell. Finally the stage “Calculation of production parameters” has the purpose of calculate Cycle times, production rates, utilizations to can compare the improvement in relation with old production process or if the product has never been manufactured to can obtain good results and compare them in the future with others production process.

For the Tesla Turbine the reduction of the Cycle time in percentage was 13.21%, therefore there was an increase in the production rate in 13.21%. Also every station increased its utilization with the new production process.
The production process of a Stirling Motor was created using the same configuration that was used with the Tesla Turbine and the cycle time obtained was 37 minutes and 45 seconds approximately.

Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

1.1.1 Literature Review

Manufacturing companies have new challenges in a globalized and competitive manufacturing environment. To be successful, it is needed to develop new manufacturing systems to accomplish customer's requirements, which are mainly oriented in low cost and time delivery. This vision suggests considerable changes in manufacturing enterprises. In order to compete effectively, manufacturing companies require to develop new manufacturing systems costly and timely effective.

a. Manufacturing systems life cycle

The significant reduction in product development time as a result of the use of CAD tools was not paralleled in the design and development of manufacturing systems. These systems must be designed to satisfy certain requirements and constraints that vary over time. Recent improvements in productivity were attributed more to improvements in the design and operation of manufacturing systems, as well as the design of products, than to manufacturing processes or technology improvements. Some modern design theories and methodologies, such as the design axioms [1,2] have been applied to the design of manufacturing systems. In the context of manufacturing systems, one can visualize a life cycle [3,4], as outlined in Figure 1.1, which includes the initial system design and synthesis, modeling, analysis and simulation, realization and implementation, operation, and re-design/reconfiguration phases. Both soft and hard reconfiguration and flexibility can extend the utility, usability, and life of manufacturing systems.

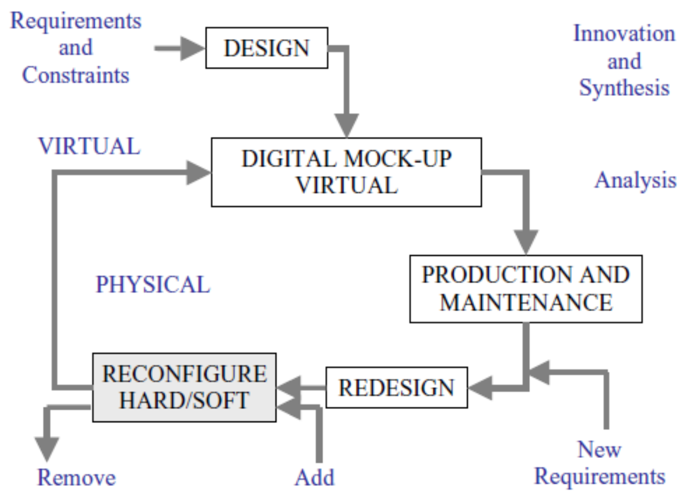


Figure 1.1 Manufacturing systems life cycle (ElMaraghy, 2000)

b. Agile Manufacturing

Agile manufacturing has become a manufacturing paradigm in the last years. However, it is difficult to find a common agreed definition for it. For example, [5] presented several definitions such as the ability to thrive in a competitive environment of continuous and unanticipated change and respond quickly to changing markets; another given definition is the responsibility-based manufacturing; [6] stated that Agile Manufacturing focuses on rapidly setting up the whole organization for producing different products. Agile manufacturing makes emphasis on doing all tasks rapidly using various parts of the organization, all of whom are flexible and responsive.

Then, Agile manufacturing takes the concept of flexible manufacturing to a higher plane, extending the concept to the whole organization, thus a key characteristics of an agile organization is flexibility [7]. Some of the common characteristics of Agile Manufacturing are [6]:

- Flexible production technologies
- A knowledgeable and involved work force
- Open management practices
- Rapid product and process development
- Partnerships with suppliers and competitors

A major challenge of agile companies developing new products is the creation of reconfigurable manufacturing system [8]. The capability for rapid development of the manufacturing system depends on two factors: i) the manufacturing system needs to be highly flexible such it minimizes the changes required to produce a new product; ii) the requirements for a manufacturing system that will produce the new product need to be validated to ensure error-free production. Research related to Agile Manufacturing reflects a clear trend to develop projects related in the supply phase of the product life cycle; while there is no much research about topics such as the product and manufacturing systems design, process planning and facilities design [9]. Early stages analysis of a manufacturing system development will involve extensive use of computer modeling design validation. The initial vision of agile manufacturing identified the "increasingly" intensive computer modeling of processes with a view to eliminating pilot plants [6].

Agile manufacturing systems are created as a solution to manufacturing environment with an unpredictable and dynamic demand, and with a high degree of mass customization in its products [9]. The key characteristics of agile manufacturing include [5]:

- Virtual enterprise formation tools/metrics
- Physically distributed manufacturing architecture and teams
- Rapid partnership formation tools/metrics
- Concurrent engineering
- Integrated product /production business information system
- Rapid prototyping
- Electronic commerce

Agile manufacturing is an extended concept of flexible technologies and the alignment of all the resources within the organization to response in an unpredictable manufacturing environment. Agile manufacturing requires new technologies that support the life cycle product in order to fulfill the customer requirements, such as reconfigurable manufacturing systems technologies [5].

c. Flexible Manufacturing systems

Flexible Manufacturing Systems (FMSs) are one of the latest levels of automation to achieve more productivity and flexibility from manufacturing equipment. A FMS is defined as a collection of production equipment logically organized under a host computer and physically connected by a central transport system. The objective of the FMS is to simultaneously manufacture a mix of part types being flexible enough to sequentially manufacture different part mix without high cost, time, and changeover requirements [10]. Another definition of FMS has been given by [11] where it is defined as a production system consisting of a set of identical and/or complementary numerically controlled machines which are connected through an automated transportation system. Another definition is given by [12] where define a FMS as a system dealing with high level distributed data processing and automated material flow using computer-controlled machines, assembly cells, industrial robots, inspection machines, together with computer integrated material-handling and storage systems. An FMS is capable of processing work-pieces of a certain mix in an arbitrary sequence with negligible setup delays between operations. In a FMS a set of preadjusted tools is available through a centralized tool magazine with direct access. FMSs can be configured to be process- or product-oriented. The main advantages of a FMS rely on being able to adapt well to most changes in the production.

Numerous goals are pursued by FMSs, typically the personnel costs reduction, increase of machine utilization, process time reduction for orders and lower inventory and capital costs. The FMSs aims the combination of advantages of a conventional quick change of production tasks with high capacity and low cost unit [11].

Some other factors to adopt FMS in manufacturing are the increased competition, market response improvements and flexibility in production [13].

The major problems faced implementing FMS are [12]:

- Partially obsolete facilities
- Incompatibility between systems
- Facilities with mixed processing

• Dynamic volume and mix
• Varieties of process options

Some characteristics of flexible manufacturing systems are that machines are laid out in a predetermined layout to simplify and minimize material movement. FMSs fail to deal with long-term changes in the demand due to its predetermined capacity; they need high investment in machine installation and relayout; they are imbalanced of utilization of machines and labor and they present significant difficulty in incorporating the impact of dynamic operational factors into system design [14]. Then, a FMS can produce a variety of products, with changeable volume and mix, on the same predetermined capacity. FMS consists of expensive, general-purpose computer numerical controlled machines. FMSs are constructed with all possible functionality built in and it should be able to produce any part (within the machine envelope), at any mix of parts and in any sequence. This approach increase the cost related to investment by the installation of all possible functionality, requiring general purpose machines and multiple set of tools, making FMS a very expensive solution [15].

d. Dedicated Manufacturing Lines

Dedicated Transfer Lines (DMLs) consist of several hundred interconnected process tools/machines. Each tool/machine within the system is highly specialized and performs one or two tasks. Material flow from one process tool to another is automated; the sequence of the flow is fixed, predetermined and it cannot be altered without stopping the system [16]. [17] reported that DMLs are based on inexpensive fixed automation and produce a high volume product. The structure of a DML is of a linear network of service stations or machines separated by buffer storages; they are generally used in high volume production [18]. These types of manufacturing lines are called transfer machines or transfer lines. According to the main characteristics of a DML are:

• A series of closely spaced production stations are linked by material-handling devices to move the parts from one machine to the next.

• There is a sequential production process, with each station performing one of the process steps.

• The number of stations in the system is dictated by the complexity of the production process implemented.

DML are not scalable because their fixed and one-part oriented design. Thus, a DML is not designed for variable cycle times or to produce a mix of products.

e. Reconfigurability

Reconfigurability has been an issue in computing and robotics for many years. In general, reconfigurability is the ability to repeatedly change and rearrange the components of a system in a cost-effective way.

Nowadays, the market is characterized by over-capacity and large fluctuations in demands. Therefore, today's manufacturing systems should enable flexibility in capacity, responsiveness in market changes, product variety, adoption and utilization of new technologies, and general scalability, in a cost effective manner.

Cost in DMLs is low, as long as they operate at full capacity. This means that demand should exceed supply. Furthermore, DMLs are not scalable, as they have defined cycle times and capacity [15]. Clearly, DMLs do not offer an efficient solution for the current market conditions.

Designed around a fixed set of part families, CMSs are oriented towards stability of demand and long life cycles. Therefore, increased product variety is difficult to be achieved, as CMSs are structurally inflexible and the redesign of the cells or changing the shop floor layout is too costly [19]. Subsequently CMSs are not economic for fluctuations in volume.

On the other hand, the FMSs are flexible, scalable systems that support product variety. They are, however, rather complex as they are constructed with all possible functionality built-in despite of the fact that in many cases not all of it is needed. This level of complexity requires highly skilled personnel to be employed. As a result, the capital costs and the acquisition risk are very high. Additionally, although FMSs focus on flexibility, they are obsolete, as their hardware and software are predetermined and fixed [20,21]. This means that they are not adequately responsive to change, as their capabilities in terms of upgrading, add-ons and customization are limited. Moreover, FMSs were built for low or medium volume productivity, so they are not suitable for large market fluctuations.

Table 1.1 Summarizes the weaknesses of DMSs, CMSs. and FMSs.

Table 1.1 Disadvantages of conventional manufacturing paradigms

DMS	CMS	FMS
Inflexible	Inflexible	
Fixed capacity	Fixed capacity	Low throughput
Fixed variety	Fixed variety	Complex
Not scalable	Machine duplication	Expensive
Not responsive	Not responsive	Not responsive
Obsolete	Obsolete	Obsolete

The new paradigm needed by today's manufacturing should incorporate the advantages of FMS but also be simpler, responsive, and less costly. The Reconfigurable Manufacturing Systems (RMS) paradigm attempts to satisfy these requirements and avoid the shortcomings of the previous conventional manufacturing philosophies.

It can be noted that there are sufficient common grounds in philosophy and application between the FMS and RMS paradigms to support the notion that they represent. It can be seen in the Table 1.2.

Table 1.2 Characteristics of dedicated, flexible and reconfigurable manufacturing systems [22]

	Dedicated	RMS/RMT*	FMS/CNC
System structure	Fixed	Adjustable	Adjustable
Machine structure	Fixed	Adjustable	Fixed
System focus	Part	Part Family	Machine
Flexibility	No	Customized	General
Scalability	No	Yes	Yes
Simultaneous operating tools	Yes	Yes	No
Cost	Low	Intermediate	High

f. Need for the RMSs

Traditional manufacturing systems fail to satisfy the needs of today's requirements. Next generation manufacturing system aims at achieving rapid changes in process technology which are highly productive, flexible and are easily upgradable to accommodate new technologies and functions. The current environment demands shorter lead times, more customization, low and fluctuating volumes, low price, etc. from a new manufacturing system [23].

Reconfigurable Manufacturing System aims at meeting these demands. RMS is considered as the next manufacturing paradigm which uses modular equipment as building blocks for the production of the part family. They incorporate customized flexibility in terms of scalability and reconfiguration as opposed to the general flexibility in FMSs [3].

g. Characteristics of the RMSs

Following are the key characteristics that RMSs must possess. These characteristics are outlined by Koren et al. [1999]. The manufacturing system which possesses these characteristics can be assumed to have high level of reconfigurability.
Customization and Convertibility tends to reduce the reconfiguration cost whereas Modularity, Integrability and Diagnosability reduce reconfiguration time in addition to the cost.

- **Modularity**

  Modularity refer to subdivision of production functions and requirements into operational units which can be maneuvered between alternate production schemes to achieve the optimal result. In RMSs all major components are modular. These components can then be replaced or upgraded to suit new environment. The maintenance of these modules is easy which helps in lowering life-cycle costs of a system.

- **Integrability**

  Integrability is the ability to integrate modules rapidly and precisely so that the modules communicate with each other. For e.g. Axes of motion and spindles can be integrated to form machines. Clusters of part features and their corresponding machine operations are related to the machine modules to enable product-process integrations. The integrated system performance is calculated based upon the performance of its components and the modules of software and hardware.

- **Customization**

Customization has two aspects – customized flexibility and customized control.
Customized flexibility refers to the designing of machine/system flexibility to just around the product family which can then be altered anytime to obtain required flexibility. This major difference between a RMS and a FMS allows drastic reduction in investment cost. This enables the design of a system for production of whole part family rather than a single part. Customized control is achieved by integrating control modules which provide exact control functions needed.

- **Convertibility**

Convertibility refers to the ability to carry out quick changeover between existing products and quick system adaptability for future products. It transforms functionality of existing systems, machines and controls to suit new production requirements. Conversion requires changing tools, part–programs and fixtures, manual adjustments of degree of freedom and can also take into account changes when switching production between two members of part family.

- **Diagnosability**

Dignosability refers to the detection of unacceptable part quality for reducing the ramp up time in RMS. It is the ability to read the current state of system for detecting defects in output and subsequently correct those defects quickly. Diagnosability has two aspects – detecting machine failure and detecting non-conforming part quality. As production systems are made more reconfigurable, it is necessary to rapidly ramp–up newly reconfigured system so that it produces quality parts. Therefore, RMSs are designed with product quality management systems as an integral part.

h. Manufacturing Operations

There are certain basic activities that must be carried out in a factory to convert raw materials into finished products. Basically the factory activities are:

1. Processing and assembly operations
2. Material handling
3. Inspection and test
4. Coordination and control

Processing and assembly operations alter the geometry, properties, and appearance of the work unit. They add value to the product. The product must be moved from one operation to the next in the manufacturing sequence, and it must be inspected and tested to ensure high quality. It is sometimes argued that material handling and inspection activities do not add value to the product. However, material handling and inspection may be required to accomplish the necessary processing and assembly operations, for example, loading parts into a production machine and assuring that a starting work unit is of acceptable quality before processing begins.

- **Processing and Assembly Operations**

  Manufacturing processes can be divided into two basic types: (1) processing operations and (2) assembly operations. A processing operation transforms a work material from one state of completion to a more advanced state that is closer to the final desired part or product. It adds value by changing the geometry, properties, or appearance of the starting material. An assembly operation joins two or more components to create a new entity, which is called an assembly, subassembly, or some other term that refers to the specific joining process. Figure 1.2 shows a classification of manufacturing processes and how they divide into various categories.

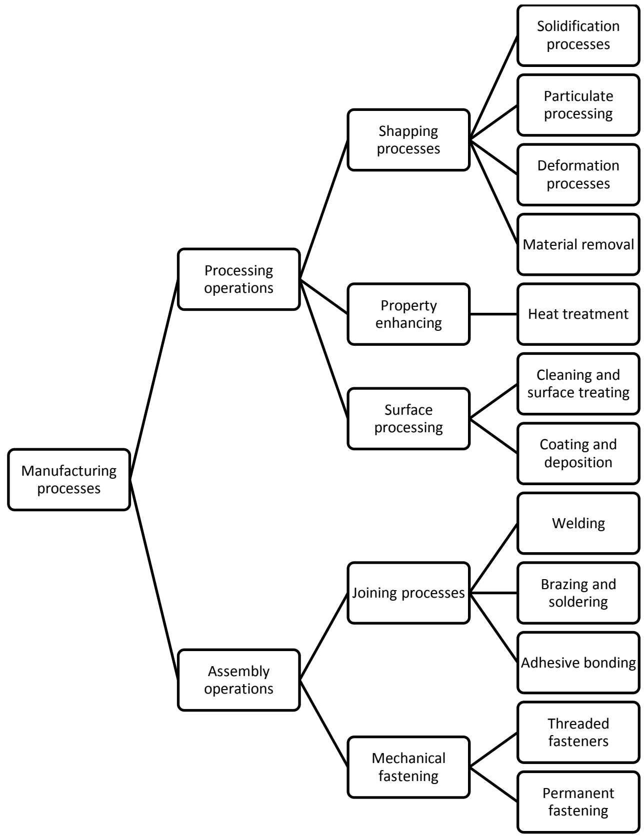


Figure 1.2 Classification of manufacturing processes [24]

- **Other factory Operations**

Material Handling and Storage. A means of moving and storing materials between processing and assembly operations is usually required. In most manufacturing plants, materials spend more time being moved and stored than being processed. In some cases, the majority of the labor cost in the factory is consumed in handling, moving, and storing materials. It is important that this function be carried out as efficiently as possible.

Inspection and Testing. Inspection and testing are quality control activities. The purpose of inspection is to determine whether the manufactured product meets the established design standards and specifications. For example, inspection examines whether the actual dimensions of a mechanical part are within the tolerances indicated on the engineering drawing for the part. Testing is generally concerned with the functional specifications of the final product rather than with the individual parts that go into the product. For examples, final testing of the product ensures that it functions and operates in the manner specified by the product designer.

Coordination and Control. Coordination and control in manufacturing include both the regulation of individual processing and assembly operations and the management of plant level activities. Control at the process level involves the achievement of certain performance objectives by properly manipulating the inputs and other parameters of the process.

Control at the plant level includes effective use of labor, maintenance of the equipment, moving materials in the factory, controlling inventory, shipping products of good quality on schedule, and keeping plant operating costs to a minimum. The manufacturing control function at the plant level represents the major point of intersection between the physical operations in the factory and the information processing activities that occur in production.

i. Productivity

Productivity is a scientific concept, in the sense that it can be logically defined and empirically observed. It is also measurable in quantitative terms, which qualifies it as a "variable". Like most scientific variables (such as density or pro-capita income), productivity can be defined and measured in absolute or relative terms. A suitable definition of absolute productivity is the quantity of physical work produced by a unit of labor directly engaged in its production.

By this definition, productivity in a construction project would be measured in tons of steel erected per work-hour or meters of pipe installed per work-hour; these are simply the inverse of what industrial terminology define as "installation unit rates" or "labor unit rates"

An absolute definition of productivity is not very useful. Much more useful, and widely used in industry, is the concept of relative productivity or productivity factor (PF), defined as the ratio of the quantity of physical work produced by a unit of labor on a specific project and activity, to the quantity of the same work produced by a unit of labor on a standard project in standard conditions. Note that, by this definition, productivity is the inverse of what industry defines as “labor factor” (LF) (work-hours per unit of work completed, divided by the corresponding “standard” work-hours).

Productivity should not be confused with competitiveness or profitability, which are directly affected by it, but are also influenced by other unrelated factors, such as raw materials costs, transportation costs, overhead, financial costs, and taxation.

Like most variables in economics and management sciences, productivity is not easy to measure, and can only be measured indirectly, that is, by measuring other variables and then calculating productivity from them.

Measuring the productivity factor (PF) for an activity involves three necessary steps:

- Measuring physical work performed (typically, quantities installed or produced);
- Measuring the work-hours to complete it, thereby calculating the actual labor unit rate; and
- Relating the actual labor unit rate to the standard unit rate:

  Productivity Factor PF= Standard Labor Unit Rate/ Actual Labor Unit Rate, or:

  Labor Factor LF= Actual Labor Unit Rate / Standard Labor Unit Rate

Productivity is a measure of the efficiency of production. Productivity is a ratio of production output to what is required to produce it (inputs). The measure of productivity is defined as a total output per one unit of a total input.

1.1.2 Evolution Process

Manufacturing in its earliest form was carried out by single skilled artisans. Before the industrial revolution, most of the manufacturing was carried out in rural areas where it augmented the occupation of agriculture. First systematic study of manufacturing was carried out in 1911 by Frederick Taylor in his classic “The Principles of Scientific Management” where he analyzed work flows to improve labor productivity [25]. From then the concept of manufacturing has evolved taking the form of well-developed system. Modern manufacturing can be classified according to the various types of techniques it implements. Following is a brief overview of the types of Manufacturing Systems:

- Mass Production

  It is a manufacturing technique which enables the production of standardized products in high volume having low cost per unit. The disadvantage of this system is that it tends to be very inflexible and cannot account for changes in production process or design [26].
- Lean Manufacturing

  It is a manufacturing practice which aims to eliminate waste at every stage of manufacturing. Anything which does not add value to the final product is considered as waste and every effort is considered to eliminate it. Optimum quality can be guaranteed as each part is inspected as it is manufactured [27].
- Cellular Manufacturing (CMS)

  It is a manufacturing system wherein equipments and workstations are efficiently arranged and grouped into cells to have smooth and continuous flow of inventory. A set of given products are manufactured completely from start to finish in a specific cell which caters to the set that undergo same production process [28]
- Flexible Manufacturing

  A typical Flexible Manufacturing System (FMS) consists of a group of computers controlled by independent workstations or machines that are able to accommodate wide variations in types and quantities of products. FMS is highly flexible in managing manufacturing resources like time and effort in order to manufacture a new product [29].
- Reconfigurable Manufacturing

  It is a manufacturing technique which allows repeated changes and rearrangements of the components of a manufacturing system in a cost –effective way. The key features of this system are that it provides modularity, integrability, customization, convertibility and diagnosability to a manufacturing system. Reconfigurable Manufacturing System (RMS) allows for adding, removing or modifying specific process capabilities, controls, softwares or machine structure to adjust production capacity in response to changing market demands or technologies [30]. The main difference between RMS and FMS is that RMS provides quick customized flexibility on demand while FMS provides generalized flexibility for a predetermined variation [4].

1.1.3 Definition of Reconfigurable Manufacturing Systems

RMS was introduced in the mid-nineties as a cost-effective response to market demands for responsiveness and customization. RMS has its origin in computer science in which reconfigurable computing systems try to cope with the inefficiencies of the conventional systems due to their fixed hardware structures and software logic.

According to [15], "A reconfigurable manufacturing system (RMS) is designed at the outset 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 or in regulatory requirements". Furthermore, as argued in [31] "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. This type of system provides customized flexibility for a particular part-family, and will be open-ended, so that it can be improved, upgraded, and reconfigured, rather than replaced".

The concept of product families is yet employed in reconfigurable manufacturing. As stated in [32], each configuration of the RMS corresponds to the production of one product family. Thus, large product variety could be achieved through the application of several configurations.

Part family: A part family is defined as one or more part types with similar dimensions, geometric features, and tolerances, such that they can be produced on the same, or similar, production equipment.

Others Definitions of RMSs

- A Reconfigurable Manufacturing System is designed at the outset 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 or in regulatory requirements [15].

- A Reconfigurable Manufacturing System is designed for rapid adjustment of production capacity and functionality, in response to new circumstances, by rearranging or change of its components [33].

RMS along with one of its components called Reconfigurable manufacturing Tool was invented in 1999 at the Engineering Research Center for Reconfigurable Manufacturing Systems (ERC/RMS) at the University of Michigan, College of Engineering. The RMS goal is summarized by the statement – *Exactly the capacity and functionality needed, exactly when needed* [15]. RMSs can be easily and quickly created by using the pre-produced basic process modules viz. hardware and software. With addition, removal or modification of these process modules being easy, RMSs can be upgradable to cater any requirements [33].

1.1.4 State of the Art

A key component of a Reconfigurable manufacturing system are the reconfigurable machine tools

- **Reconfigurable machine tools**

The RMT is a kind of application-oriented machine tool, whose manufacturers, suppliers and end users are demanding much more resource to form the supply chains with low cost, high quality and fast delivery, but researches on RMT are still at the design stage.

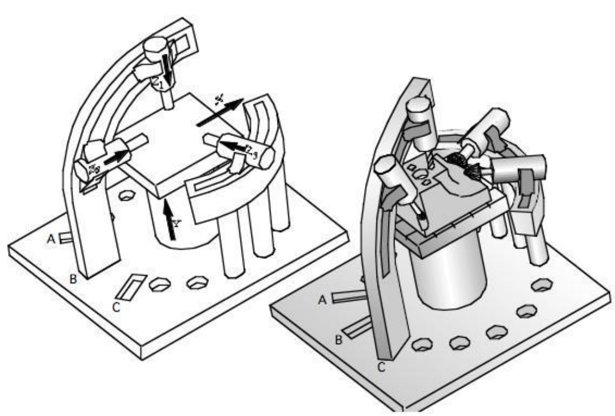


Figure 1.3 Reconfigurable machine tools

1.2 Justification

One problem in the manufacturing systems is the idle time in the stations caused by a wrong or inefficient design of the production process of a determined product. Other problem is run the production process without have simulated it in a software because it can cause unnecessary costs.

1.3 Hypothesis

It's possible to improve the production rate of a product in a Reconfigurable Manufacturing System or even propose a very good production process of a new product in the RMS and obtain a very good production process for a Stirling Motor using the same configuration that was used to manufacture the Tesla Turbine only adding a manual station.

1.4 Objectives

- Evaluate the production of a Tesla Turbine in a RMS and improve the production rate.
- Design the production process of a Stirlig Motor with the same configuration that the used with the Tesla Turbine only adding a Manual Station. Evaluate the production of a Stirling Motor in the RMS.
- Simulate through Plant Simulation the production of the Tesla Turbine and Stirling Motor to view statistic and validate the results.

1.5 Thesis organization

The research presented is organized in six chapters described below:

- Chapter 1 – Introduction. The characteristics of the Reconfigurable Manufacturing Systems and literature review analysis about productivity are presented.
- Chapter 2 - The methodology applied to evaluate and improve the production rate and utilization of the stations in a reconfigurable manufacturing system is presented.
- Chapter 3 - Two study cases are shown describing how the methodology is implemented. Simulations of the two cases are presented.
- Chapter 4 - Conclusions and future researchs are presented.
- Chapter 5 - References

2 Methodology

The objective can be reached through the development of three main stages. The first stage "Obtaining of operations times" has the purpose of get the times of each operation involved in the production process. The second stage "Definition of the Process Flow" has the purpose of define the number of pallets, their contents and their flows in the Manufacturing Cell. Finally the stage "Calculation of production parameters" has the purpose of calculate Cycle times, production rates, utilizations to can compare the improvement in relation with old production process or if the product has never been manufactured to can obtain good results and compare them in the future with others production process.

The three main processes used in this methodology to improve the production rate of a product or to design an appropriate production process of a new product in a flexible or reconfigurable manufacturing system are:

- Obtaining of operations times.
- Definition of the Process flow.
- Calculation of production parameters.

2.1 Obtaining of operations times

First at all, two concepts are described to can have a better understanding of the methodology: Measurement of times and flow diagram.

Measurements of times

The measure or obtaining of times in the production systems is very important because these are the base to can start to evaluate the whole system and detect which is the bottleneck, what is the stations with more idle time, which is the slowest process and so on. Each operation (transportation, assemblies, machining, handling material, etc) has to be measured with a chronometer.

Flow diagram

A flow diagram is a graphical means of presenting, describing, or analyzing a process. This is done by drawing small boxes which represent steps or decisions in a chain of steps or decisions. These boxes are connected to other boxes by lines and arrows which represent sequence and dependency relationships.

After these two concepts we proceed with the methodology:

If there is a product and the objective is improve the actual production process reducing the cycle time, the steps to follow are:

- Obtain times of transportation, times of machining, times of material handling, times of load and unload, times of assembly and other important times involved in the production.
- Once obtained all the times involved in the production, make a table with the description of these times and name these with a symbol.
- Make a flow diagram of the production process of the product to can visualize more clearly the process and detect improvement opportunities.
- Obtain the workload of the stations, cycle time, production rate and utilizations of the stations to have a reference. For the explication of this process go to the Bottleneck model.

If the product has never been made in the cell,

- The first step that have to be made is define what parts will be machined in the CNC stations, simulate the machining in a software and obtain the times.
- Obtain times of transportation (from one station to other station), these times can be obtained measuring the transportation times of other products in the same cell and with the same configuration.
- Go the point called "Definition of the Process Flow"

2.1.1 Bottleneck Model [24]

The term bottleneck refers to the fact that the output of the production system has an upper limit, given that the product mix flowing through the system is fixed. The model can be applied to any production system that possesses this bottleneck feature, for example, a manually operated machine cell or a production job shop. It is not limited to flexible manufacturing systems or reconfigurable manufacturing systems.

Terminology and Symbols. Let us define the features, terms, and symbols for the bottleneck model, as they might be applied to a flexible manufacturing system:

- Workstations and servers. The flexible production system has a number of distinctly different workstations. In the terminology of the bottleneck model, each workstation may have more than one server, which simply means that it is possible to have two or more machines capable of performing the same operations. Using the terms stations and servers in the bottleneck model is a precise way of distinguishing between machines that accomplish identical operations and those that accomplish different operations. Let s_i = the number of servers at workstation i, where i = 1,2,…,n.
- Process routing. For each part or product, the process routing defines the sequence of operations, the workstations where operations are performed, and the associated processing times. The sequence includes the loading operation at the beginning of processing on the FMS and the unloading operation at the end of processing. Let t_{ij} = the processing time, which is the total time that a production unit occupies a given workstation server, not counting any waiting time at the station. In the notation for t_{ij}, the subscript i refers to the station, j refers to the part or product.
- Work handling system. The material handling system used to transport parts or products within the FMS can be considered to be a special case of a workstation. Let us designate it as station $n+1$, and the number of carriers in the system (e.g., conveyor carts, AGVs, monoriel vehicles, etc.) is analogous to the number of servers in a regular workstation. Let s_{n+1} = the number of carriers in the FMS handling system.

- Transport time. The mean transport time required to move a part from one workstation to the next station in the process routing. This value could be computed for each individual transport based on transport velocity and distances between stations in the FMS, but it is more convenient to simply use an average transport time for all moves in the FMS.

FMS Operation Parameters. Using the above terms, we can next define certain average operational parameters of the production system. The workload for a given station is defined as the total time spent at the station per part. It is calculated as

$$WL_i = \sum_j t_{ij} \qquad (2.1)$$

where WL_i = workload for station i, min; t_{ij} = processing time of part j at station i, min;

System Performance Measures. Important measures for assessing the performance of a flexible manufacturing system include production rate of all parts, production rate of each part style, utilization of the different workstation, and number of busy servers at each workstation. These measures can be calculated under the assumption that the FMS is producing at its maximum possible rate. This rate is constrained by the bottleneck station in the system, which is the station with the highest workload per server. The workload per server is simply the ratio WL_i / s_i for each station. Thus, the bottleneck is identified by finding the maximum value of the ratio among all stations.

Cycle time. For any production operation, the cycle time T_c is defined as the time that one work unit spends being processed or assembled. It is the time between when one work unit begins processing (or assembly) and when the next unit begins. T_c is the time an individual part spends at the machine, but not all of this time is productive. In a typical processing operation, such as machining, T_c consists of (1) actual machining operation time, (2) workpart handling time, and (3) tool handling time per workpiece. As an equation, this can be expressed as:

$$T_c = T_o + T_h + T_{th} \qquad (2.2)$$

For the obtaining the cycle time, the times of the operations for which are passing the product have to be summed consecutively. It is important to note that when there are operations being made in parallel only the bigger time is taking in count to can calculate the cycle time.

Let WL^* and s^* equal the workload and number of servers, respectively, for the bottleneck station. The maximum production rate of all parts of the FMS can be determined as the ratio of s^* to WL^*. Let us refer to it as the maximum production rate, because it is limited by the capacity of the bottleneck station,

$$R_p^* = \frac{s^*}{WL^*} \qquad (2.3)$$

Or if this is not a mass production the production rate can be calculated as,

$$R_p^* = \frac{1}{T_c} \qquad (2.4)$$

Where R_p^* = maximum production rate of all part styles produced by the system, which is determined by the capacity of the bottleneck station, pc/min; s^* = number of servers at the bottleneck station, and WL^* workload at the bottleneck station, min/pc.

The mean utilization of each workstation is the proportion of time that the servers at the station are working and not idle. This can be computed as:

$$U_i = \frac{WL_i}{s_i}\left(R_p{}^*\right) = \frac{WL_i}{s_i}\frac{s^*}{WL^*} \qquad (2.5)$$

Where U_i = utilization of station i; WL_i = workload of station i, min/pc; s_i = number of servers at station i; and R_p^* = overall production rate, pc/min.

2.2 Definition of the Process Flow

In this part are defined the process flow determining first the number of pallets, their contents and their flows. First at all, a definition of process is presented.

Definition of Process

Sequence of interdependent and linked procedures which, at every stage, consume one or more resources (employee time, energy, machines, money) to convert inputs (data, material, parts, etc.) into outputs. These outputs then serve as inputs for the next stage until a known goal or end result is reached [34].

2.2.1 Product's parts

If there are parts that cannot be manipulated by the robot because:

- The part has no planar faces and the robot has only a planar gripper or their planar faces are smaller in dimension than the diameter of the suction cup tool that has the robot (if the part would want to be manipulated with a suction cup).
- The width, high and thickness of the part are bigger than the aperture of the gripper and it cannot be manipulated by a suction cup because of the surface of the material for example if it has smaller holes that don't let the suction cup adhere to the surface of the part.
- It's necessary make an assembly and the part has a mobile mechanism than don't let the robot make an appropriate assembly.
- The part only can be handled by a gripper but the material of the part is delicate that could be broken by the force of the gripper.
- Any other reason than doesn't let the manipulation by a robot

So send these parts to be handled by a person in a manual station

2.2.2 Process

Make processes in parallel:

- Machine a part in a station (milling machine, drill machine, turner machine, etc.) and make an assembly in other station at the same time.
- Machine a part in a station and machine other part in other station if the cell has with two or more machines.

If the product has never made before, obtain times of assembly observing the movements of the robot when assemble other products (if a robot is going to make the assembly) and approximate the time or simulate the assembly of the robot in software and obtain the time.

Once already known the parts that can be handled by a robot and those that cannot, the next step is to define the number of pallets and the arrangement of parts in the pallets.

- Put together in one or more pallets the parts that are going to be processed, machined or assembled in the same station to avoid the unnecessary transportation of the pallets in the cell.
- Don't put parts together in a pallet where some parts are going to be used in a station and other parts are going to be used in a different station, except when the all the parts will be used in a station and after of it some parts will be used in other station.
- Make a flow diagram of the production process of the product to can visualize more clearly the process.

2.3 Calculation of Production Parameters

- Applied the bottleneck model and obtain the new workload, cycle time, production rate and utilization of the stations.

3 Cases of studies

What is expected to be solved is to evaluate the process by which the products pass through, there could be different configurations for each product but in this case only one configuration is going to be evaluated.

First at all, stations have to be designed to be able to construct the whole reconfigurable manufacturing system.

The RMS is going to have the following stations:

- Milling CNC machine
- Station for manual operations
- Assembly station operated by a robot
- AS/RS system
- Handling material system
- Inspection station
- Control Station

The product to be manufactured passes for all the stations through a conveyor belt. It is important to mention that two different products will be manufactured, this is the reason why it is necessary that the cell be reconfigurable. An example of one of the possible reconfigurations with all the stations that will have the cell is seen in the Figure 3.1 and Figure 3.2.

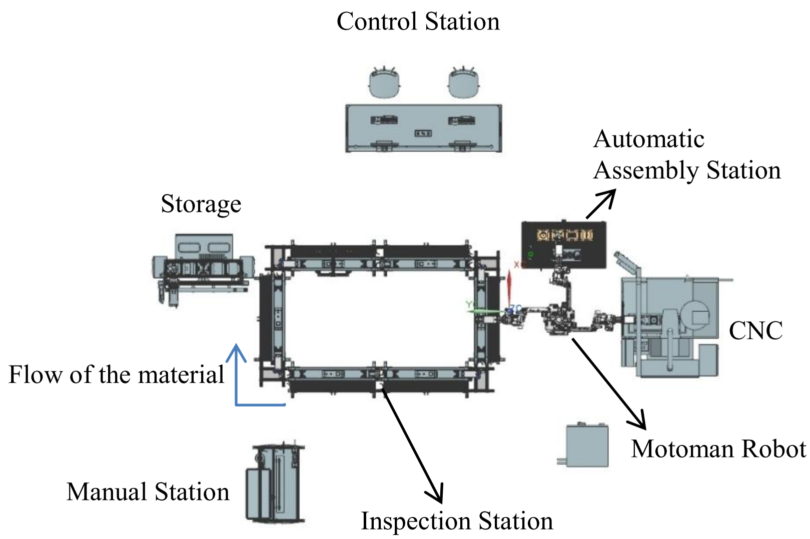


Figure 3.1 Top view of one possible layout of the cell

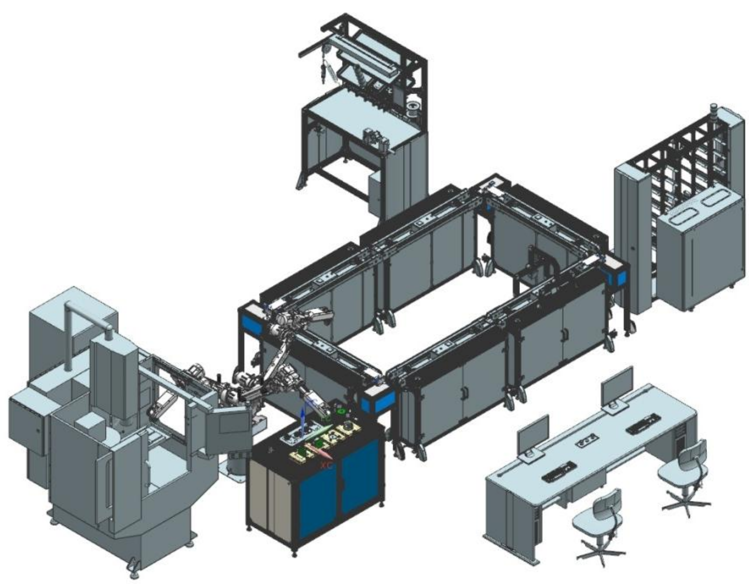


Figure 3.2 Isometric View of one possible layout of the cell

The first product to be manufactured is the Tesla Turbine.

3.1 Tesla turbine

The modeling of the turbine can be seen in the Figure 3.3 and Figure 3.4

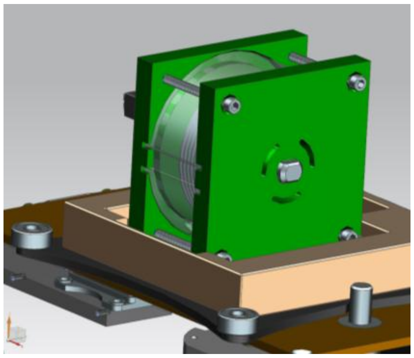


Figure 3.3 Isometric View of the Tesla turbine

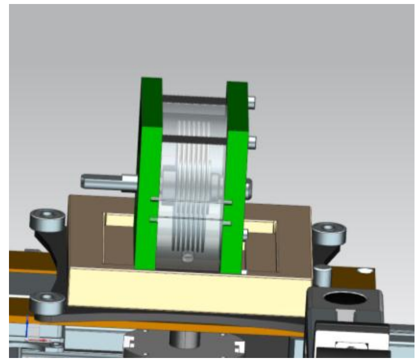


Figure 3.4 Side view of Tesla turbine

A Tesla turbine consists of a set of smooth disks, with a nozzle applying a moving air to the edge of the disk. As the air slows and adds energy to the disks, it spirals in to the center exhaust.

The Tesla turbine consists of the following parts:

- Turbine base
- Turbine cover
- Cylinder
- 4 Screws M5 x 60
- Nut
- Shaft
- 7 CDs
- 7 Washers

Next the parts are shown graphically from the Figure 3.5 to the Figure 3.12

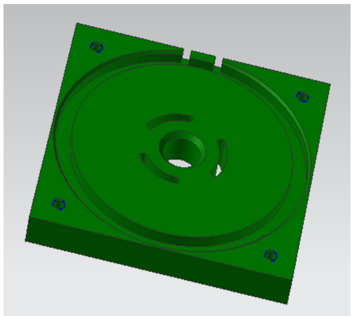


Figure 3.5 Turbine base

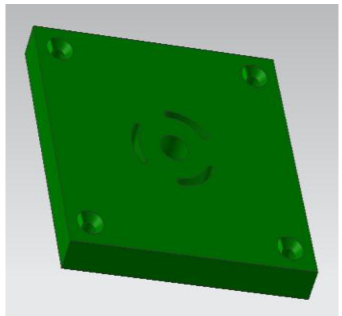


Figure 3.6 Turbine cover

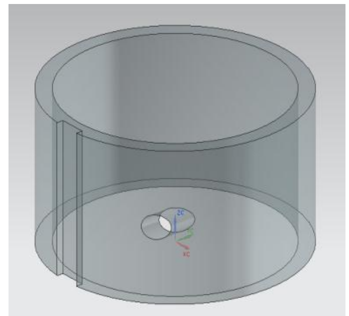


Figure 3.7 Cylinder

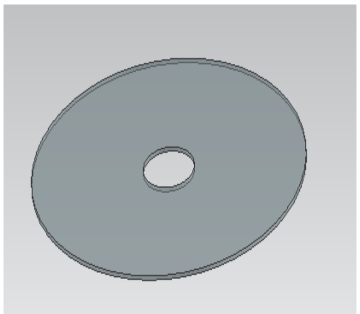


Figure 3.8 MiniCDs

Figure 3.9 Screws

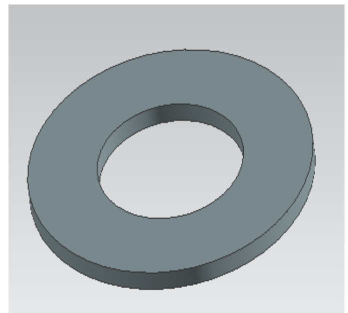


Figure 3.10 Washer

Figure 3.11Shaft

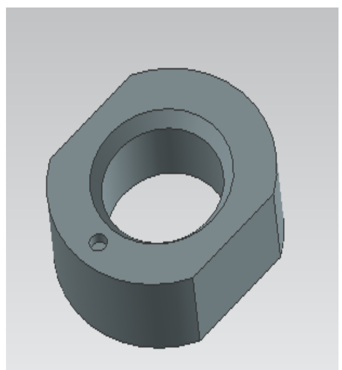


Figure 3.12 Nut

The parts that are going to be manufactured in the cell are: the turbine cover and the turbine base. The other parts are commercials and are going to be acquired by a supplier.
In this case a Robot is going to make the assembly of all the parts. Manual station will not be required.

There are going to be four pallets in the cell that are going to contain all the parts:
1st pallet: Turbine base
2nd pallet: Turbine cover
3rd pallet: CDs, washers and nut
4th pallet: Shaft, 4 Screws M5 x 60, cylinder

In the Figure 3.13 are shown the four pallets

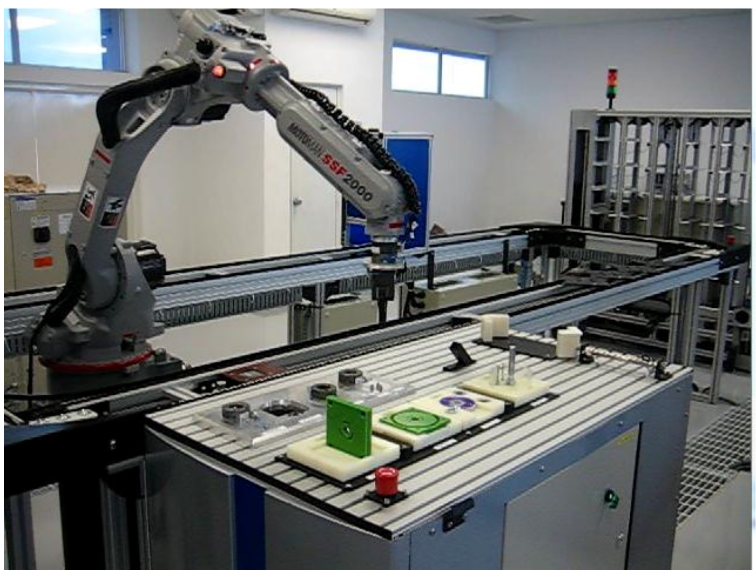


Figure 3.13 Assembly station with the four pallets

All the parts are grouped in four containers or pallets. The four pallets will be unloaded from the AS/RS system to the conveyor belt. All the parts will be taken by the robot from the conveyor belt to the Assembly station. Once the four pallets are at the Assembly station, the turbine base will be taken by the robot to the CNC Milling machine to be manufactured. It takes 100 seconds approximately to manufacture the turbine base. Then the robot takes the manufactured piece and moves it to the Assembly Station. After this the robot takes the

next pallet that contain the turbine cover and takes it to the CNC Milling machine, it takes also 100 seconds minutes approximately to manufacture the turbine cover. Then the robot takes the manufactured turbine cover and leaves it in the Assembly Station.
After this the robot makes the assembly of all the parts until the final product is done. Then the final product goes to the inspection station and finally is taken to the AS/RS system.

It takes 10 seconds approximately to make the inspection of the final product at the inspection station.
The tools that that are used for the Motoman robot to make the assembly of all the parts are:

- A gripper (shown in the Figure 3.14)
- A suction cup (shown in the Figure 3.15)
- A screwdriver (shown in the Figure 3.16)

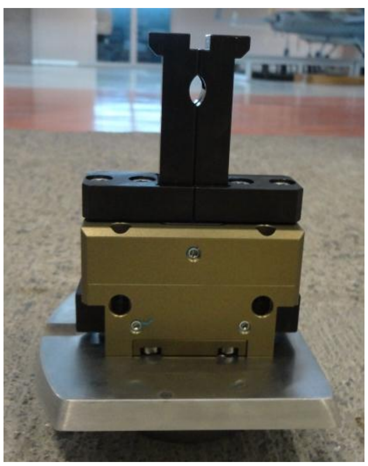


Figure 3.14 Gripper

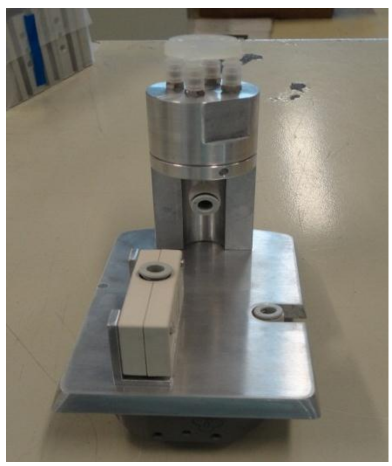


Figure 3.15 Suction cup


Figure 3.16 Screwdriver

In the Figure 3.17 is shown the flow diagram of the Tesla Turbine production and in the Table 3.1 is shown a brief Graphic Production Process of the Tesla Turbine

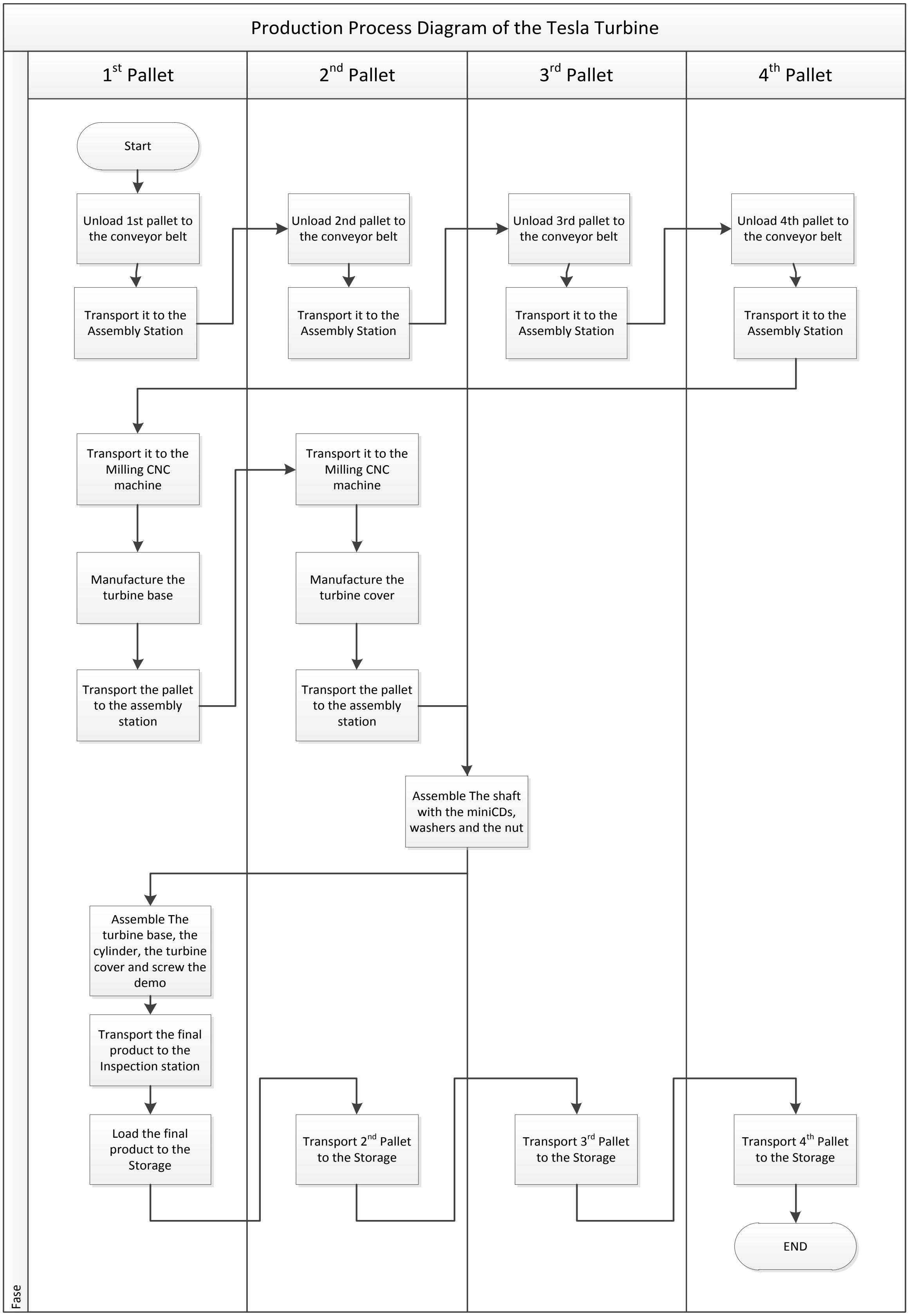
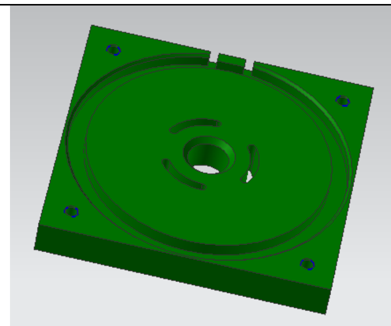
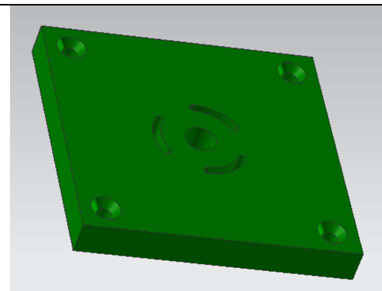
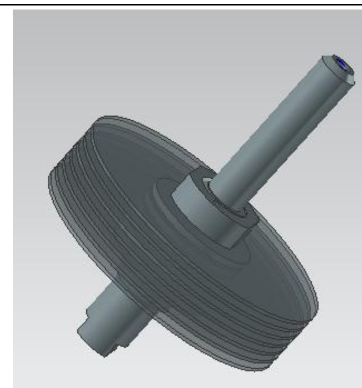
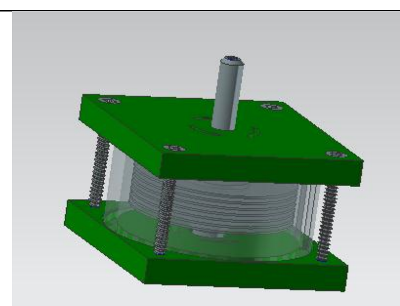


Figure 3.17 Flow diagram of the Tesla Turbine

Table 3.1 Brief Graphic Production Process of the Tesla Turbine

Process	CNC	Automatic Assembly Station
1.Machine Turbine base		
2. Machine Turbine cover		
3. Assemble the shaft with the miniCDs, the washers and the nut.		
4. Assemble the turbine base, turbine cover, cylinder and screw the demo.		

First at all we are going to show in the Table 3.2 the times wasted in each process:

Table 3.2 Operations with their respective times

Activity	Time	symbol
Unload each pallet from the AS/RS system to the conveyor belt	20 seconds	t_u
Transport time from the beginning of the conveyor belt to the Automatic Assembly station	45 seconds	t_{c-a}
Transport time from the Assembly station to the CNC Milling machine (time that the robot takes to bring the part from the automatic assembly station to the CNC Milling machine)	20 seconds	t_{a-cnc}
Manufactured time	100 seconds	t_m
Assemble the shaft with the miniCDs, the washers and the nut	150 seconds	t_{a1}
Assemble the turbine base, turbine cover, cylinder and screw the demo.	300 seconds	t_{a2}
Transport time from the Automatic assembly station to the conveyor belt	15 seconds	t_{a-cb}
Transport time from the Automatic Assembly station to the Inspection station (included the manipulation of the robot)	30 seconds	t_{a-i}
Inspection to the final pallet	10 seconds	t_i
Transport from the inspection station to the AS/RS system (no included the manipulation of the AS/RS system)	25 seconds	$t_{i-as/rs}$
Load the final product to the AS/RS system	20 seconds	t_l
Transport time from the Automatic Assembly station to the AS/RS system (included the manipulation of the robot but not of the AS/RS)	40 seconds	$t_{a-as/rs}$

According to the methodology for evaluating the productivity, we proceed of the next way: Some of the parameters used to evaluate the configuration are:

The workload for a given station is defined as the total time spent at the station per part. It is calculated as follow:

$$WL_i = \sum_j t_{ij} \qquad (3.1)$$

$$WL_{load/unload\ station} = 4t_u + 4t_l = 4(10) + 4(10) = 80\ seconds$$

$$WL_{inspection\ station} = t_i = 10\ seconds$$

$$WL_{Drill\ CNC\ station} = 2t_m = 2(100) = 200\ seconds$$

$$WL_{Assembly\ station} = t_{a1} + t_{a2} = 150 + 300 = 450\ seconds$$

$$WL_{Motoman\ Robot} = t_{a1} + t_{a2} + 4t_{a-cnc} + 4t_{a-cb} = 150 + 300 + 4(20) + 4(15) = 590\ seconds$$

For the calculus of the Cycle time we use the equation:

$$T_c = T_o + T_h + T_{th} \qquad (3.2)$$

In this case the tool handling time is included in the machining operation time, so the equation can be expressed as:

$$T_c = T_o + T_h \qquad (3.3)$$

$$T_c = t_u + 4t_{c-a} + 4 * t_{a-cnc} + 2 * t_m + t_{a1} + t_{a2} + t_{a-i} + t_i + t_{i-as/rs} + t_l + 3t_{a-as/rs} \qquad (3.4)$$

$$T_c = 20 + 4(45) + 4 * 20 + 2 * 100 + 150 + 300 + 30 + 10 + 25 + 20 + 3(40) = 1135\ seconds = 18\ minutes\ and\ 55\ seconds$$

Therefore the production rate is:

$$R_p = \frac{60}{T_c} \qquad (3.5)$$

$$R_p = \frac{60}{18.9166} = 3.1718\ pc/hr$$

The utilization of the stations is calculated as follow:

$$U_i = \frac{WL_i}{s_i}\left(R_p{}^*\right) \qquad (3.6)$$

$$U_{Load/unload\ station} = \frac{160}{60}\left(\frac{3.1718}{60}\right) = 0.14096 * 100\% = 14.096\%$$

$$U_{inspection\ station} = \frac{10}{60}\left(\frac{3.1718}{60}\right) = 0.00881 * 100\% = 0.881\%$$

$$U_{Milling\ CNC\ station} = \frac{200}{60}\left(\frac{3.1718}{60}\right) = 0.17621 * 100\% = 17.621\%$$

$$U_{Automatic\ Assembly\ station} = \frac{450}{60}\left(\frac{3.1718}{60}\right) = 0.39647 * 100\% = 39.647\%$$

$$U_{Motoman\ Robot} = \frac{590}{60}\left(\frac{3.1718}{60}\right) = 0.51982 * 100\% = 51.982\%$$

This production rate could be increased making the assembly of the shaft with the miniCDs, the washers and the nut while the turbine base and the turbine cover are being machined in the CNC. In the Figure 3.18 there is the flow diagram of this proposal reducing the cycle time and due to it increasing the production rate.

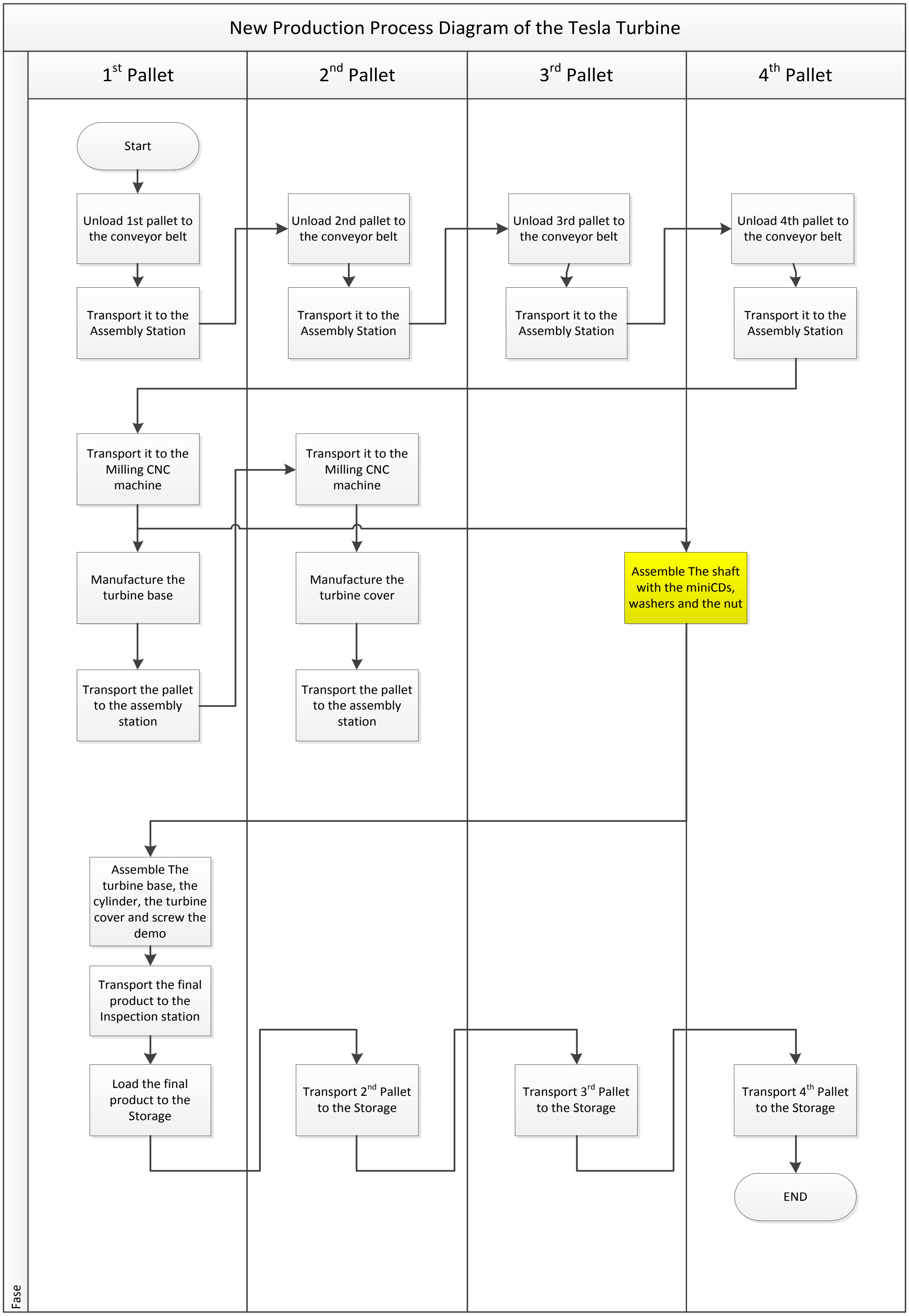


Figure 3.18 New Production Process of the Tesla Turbine

With this new process the cycle time calculated as:

$$T_c = t_u + 4t_{c-a} + 4 * t_{a-cnc} + 2 * t_m + t_{a2} + t_{a-i} + t_i + t_{i-as/rs} + t_l + 3t_{a-as/rs} \qquad (3.7)$$

$$T_c = 20 + 4(45) + 4(20) + 2(100) + 300 + 30 + 10 + 25 + 20 + 3(40) = 985\ seconds = 16\ minutes\ and\ 25\ seconds$$

Therefore the production rate is:

$$R_p = \frac{60}{T_c} \qquad (3.5)$$

$$R_p = \frac{60}{16.4166} = 3.6548\ pc/hr$$

$$U_i = \frac{WL_i}{s_i}\left(R_p{}^*\right) \qquad (3.6)$$

$$U_{Load/unload\ station} = \frac{1600}{60}\left(\frac{3.6548}{60}\right) = 0.1624 * 100\% = 16.24\%$$

$$U_{inspection\ station} = \frac{10}{60}\left(\frac{3.6548}{60}\right) = 0.010152 * 100\% = 1.0152\%$$

$$U_{Milling\ CNC\ station} = \frac{200}{60}\left(\frac{3.6548}{60}\right) = 0.20304 * 100\% = 20.304\%$$

$$U_{Automatic\ Assembly\ station} = \frac{450}{60}\left(\frac{3.6548}{60}\right) = 0.45685 * 100\% = 45.685\%$$

$$U_{Motoman\ Robot} = \frac{590}{60}\left(\frac{3.6548}{60}\right) = 0.59898 * 100\% = 59.898\%$$

It can be seen that the Motoman Robot is the station with more utilization because it makes all the assembly of the product in the Automatic Assembly Station as well as the handling material from the CNC to the Automatic Assembly Station and to the conveyor belt.

3.1.1 Results

For the Tesla Turbine, making two processes in parallel: machining the turbine base and turbine cover while the first assembly (assemble the shaft with the miniCDs, the washers and the nut) is made, reduces 2 minutes and 30 seconds the cycle time of the production. Therefore the objective of improve the production rate of the Tesla Turbine in the RMS was reached. Also this process was simulated obtaining approximately the same results that the obtained mathematically. The Figure 3.19 shows the comparison of the actual production rate and the new production rate obtained applying the methodology proposed. The new production rate increase 13.21% from the actual production rate.

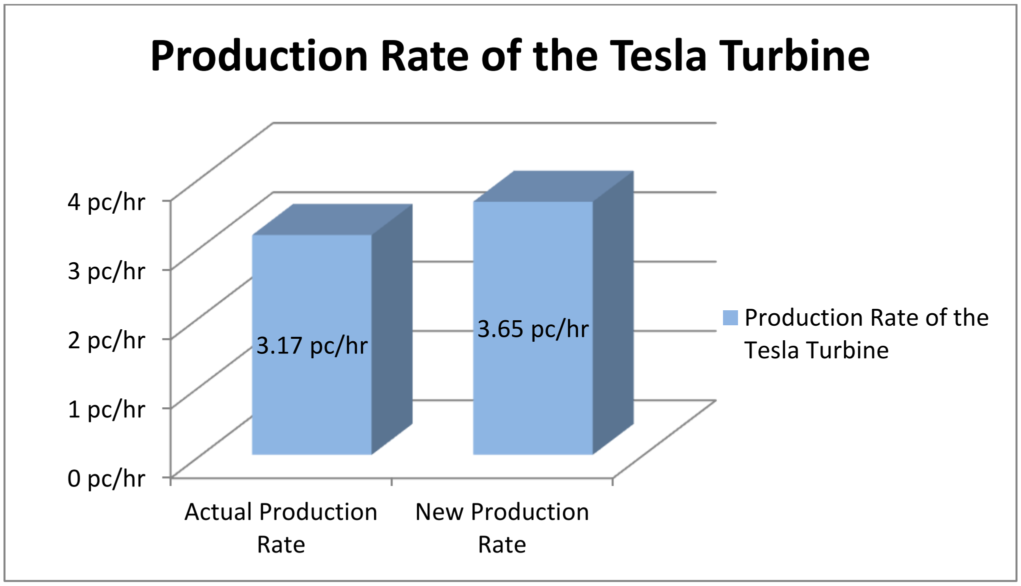


Figure 3.19 Comparison of the Actual Production Rate with the New Production Rate

The Figure 3.20 shows the utilizations of the stations with the actual production process and with the new production process. With the new process all the utilizations of the stations increase because of a reduction in the Cycle Time.

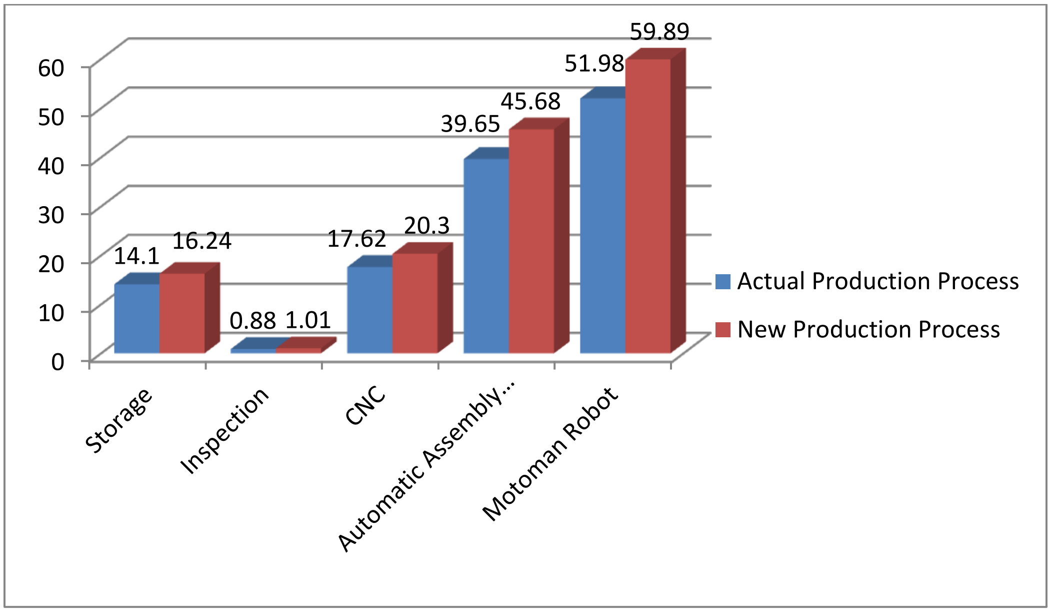


Figure 3.20 Comparison of the utilization of the stations

Simulation in the software "Plant Simulation"

The simulation was made in the software called "Plant Simulation". The new production process of the Tesla Turbine was simulated.

The parts for the Tesla Turbine were created in the frame called "Storage" that simulates the AS/RS system together with the object called "Storage Robot". The Assemblies were made in the frame called "Assembly" that simulates the Automatic Assembly Station.

The Figure 3.21 shows the configuration of the cell for the production of the Tesla Turbine

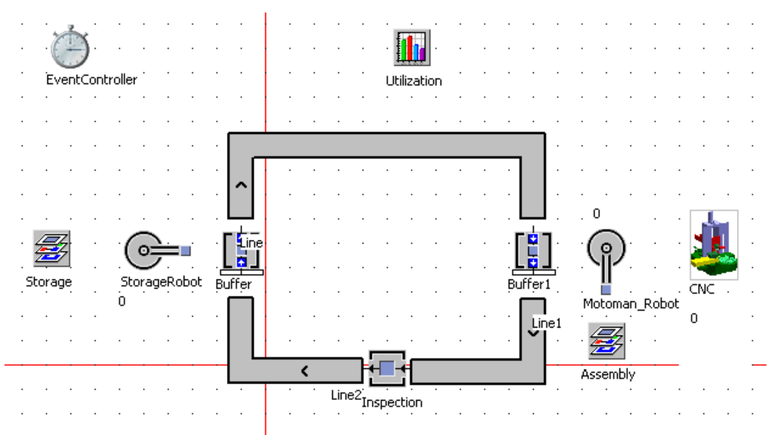


Figure 3.21 Configuration of the cell for the production of the Tesla Turbine

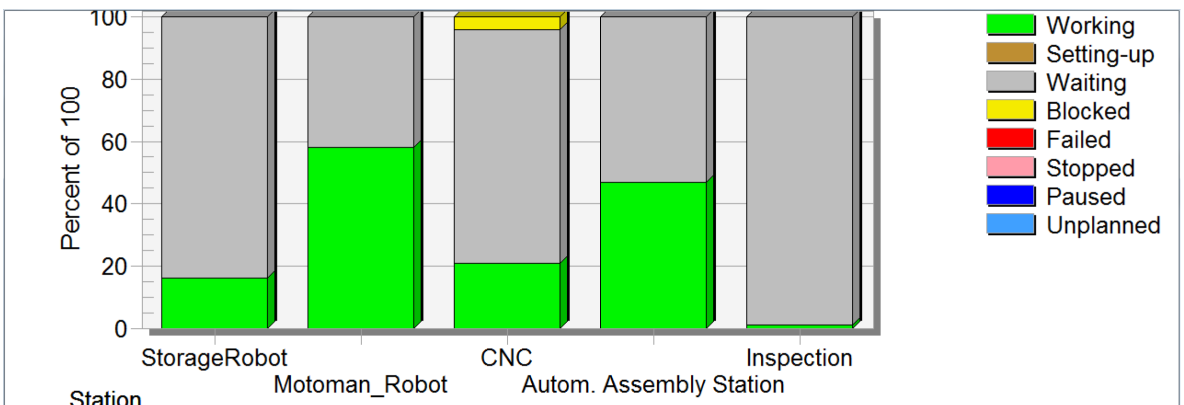
Simulation time: 16:00.0000

Object	Name	Mean Life Time
Storage.Pallet_1	Pallet1	13:41.9773
Storage.Pallet_2	Pallet2	15:41.9773
Storage.Pallet_3	Pallet3	14:21.9773
Storage.Pallet_4	Pallet4	15:01.9773

Figure 3.22 Simulation time with the Tesla Turbine

The Figure 3.22 shows the simulation time and also when each pallet comes back to the AS/RS Storage. The last pallet gets out at 15:41 approximately, so it is the Cycle Time of the production of the Tesla Turbine.

The Figure 3.23 shows the utilization of the stations in the cell. The yellow part of the CNC statistics bar means the time in percentage that the CNC is waiting for the Motoman Robot to pick up a machined part from the CNC.



Station	StorageRobot	Motoman_Robot	CNC	Autom. Assembly Station	Inspection
Working	16.23%	58.17%	20.83%	46.88%	1.04%
Setting-up	0.00%	0.00%	0.00%	0.00%	0.00%
Waiting	83.77%	41.83%	75.21%	53.13%	98.96%
Blocked	0.00%	0.00%	3.96%	0.00%	0.00%
Failed	0.00%	0.00%	0.00%	0.00%	0.00%
Stopped	0.00%	0.00%	0.00%	0.00%	0.00%
Paused	0.00%	0.00%	0.00%	0.00%	0.00%
Unplanned	0.00%	0.00%	0.00%	0.00%	0.00%

Figure 3.23 Utilization of the stations

3.2 Stirling Motor

The second product to be manufactured in the cell is a Stirling motor. The modeling of the motor can be seen in the Figure 3.24 and Figure 3.25

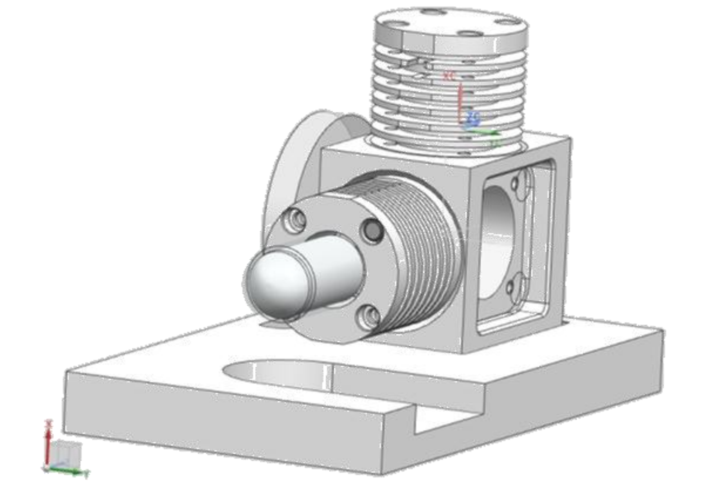


Figure 3.24 Stirling motor

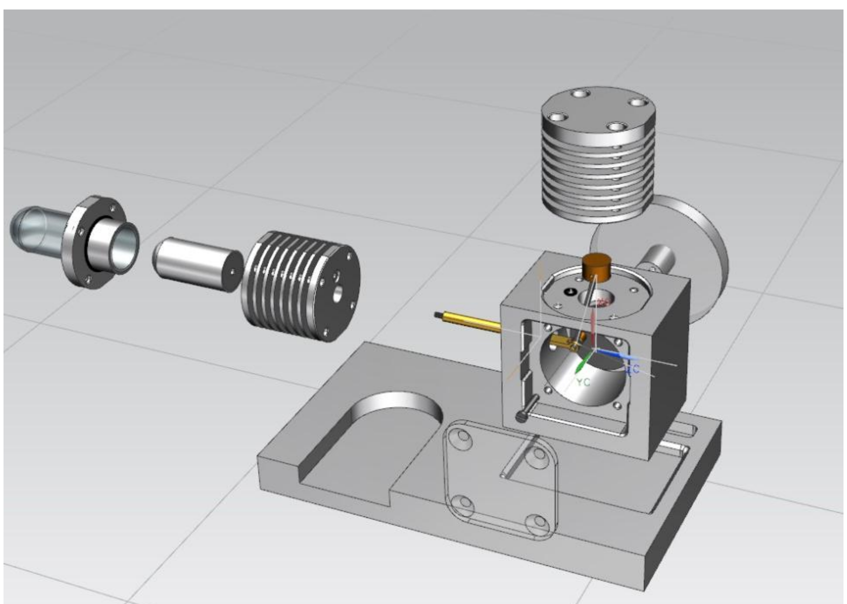
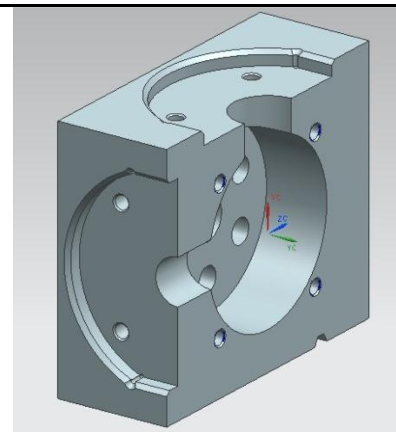
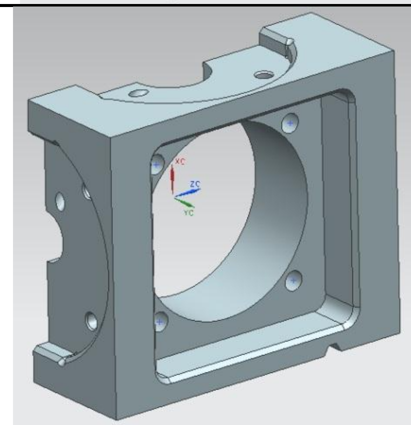
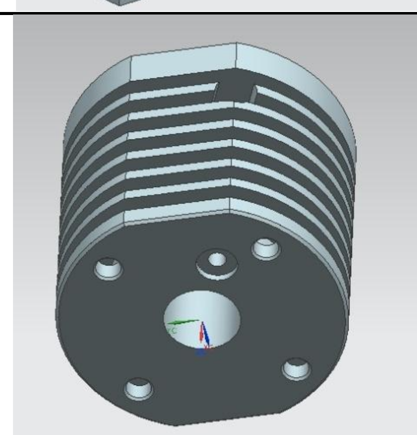
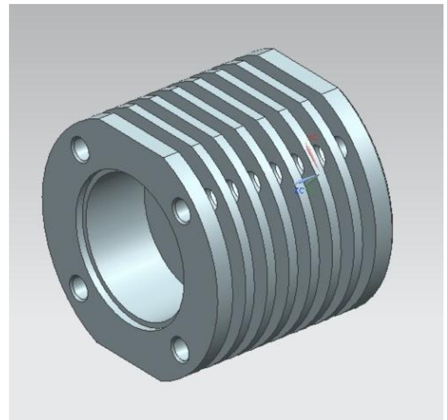
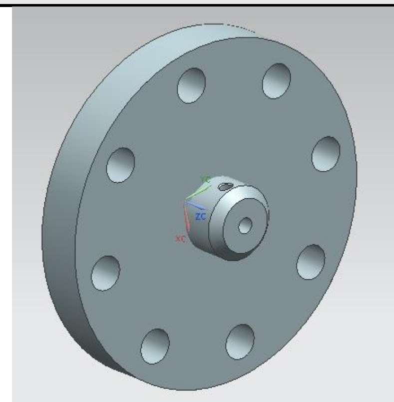
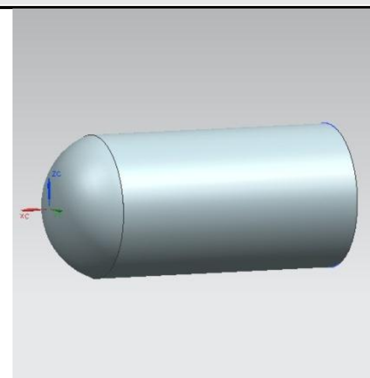
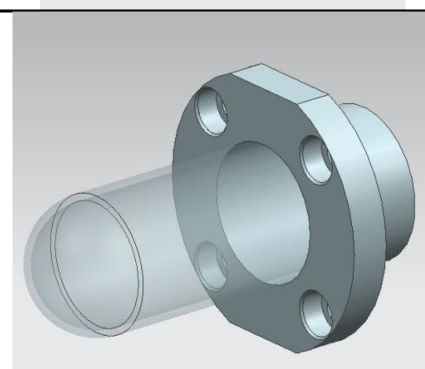


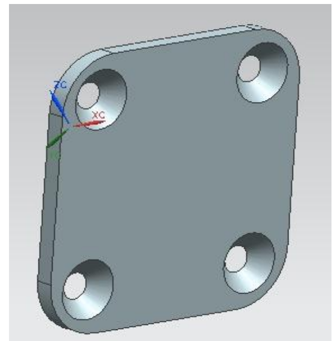
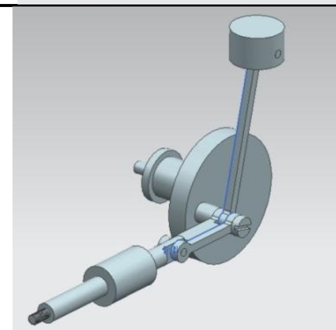
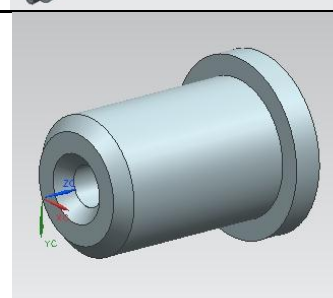
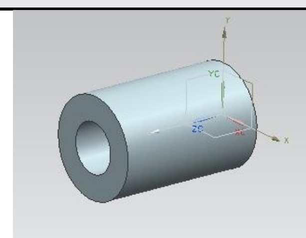
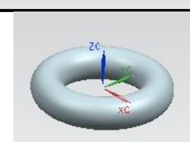
Figure 3.25 Parts of the Stirling Motor

The Table 3.3 shows the parts of the Stirling motor that are going to be premanufactured, manufactured and the parts that are going to be adquired from a supplier (commercial parts).

Table 3.3 Parts of the Stirling Motor

Half- cube 1	Pre-Manufactured and then manufactured in the cell	
Half-cube 2	Pre-Manufactured and then manufactured in the cell	
Vertical chiller	Manufactured by a supplier	

Horizontal chiller	Manufactured by a supplier	
Inertia wheel	Manufactured by a supplier	
Piston	Manufactured out of the cell	
Pyrex cover	Manufactured out of the cell	

Acrylic lid	Manufactured in the cell	
Rod mechanism	Manufactured and assembled by a supplier	
Bushing for the half-cube 1	Manufactured by a supplier	
Bushing for the horizontal chiller	Manufactured by a supplier	
2 o-rings	Commercial	
Screw for the assembly of the Inertia wheel	Commercial	

4 Head Screws socket M4	Commercial	
4 Head Screws socket M3	Commercial	
4 Countersink screws	Commercial	

The parts that are going to be manufactured in the cell are: the two half-cube and the Acrylic lid.

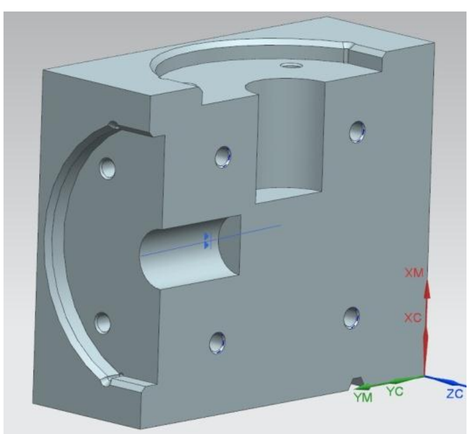


Figure 3.26 Half-cube 1 before to be machined in the cell

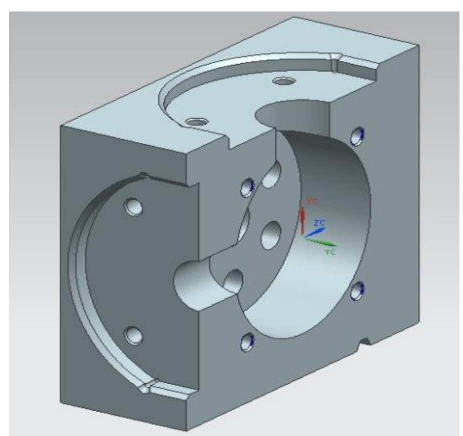


Figure 3.27 Half-cube 1 after to be machined in the cell

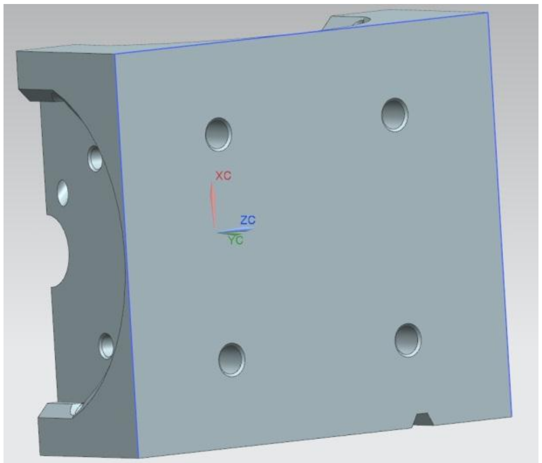


Figure 3.28 Half-cube 2 before to be machined in the cell

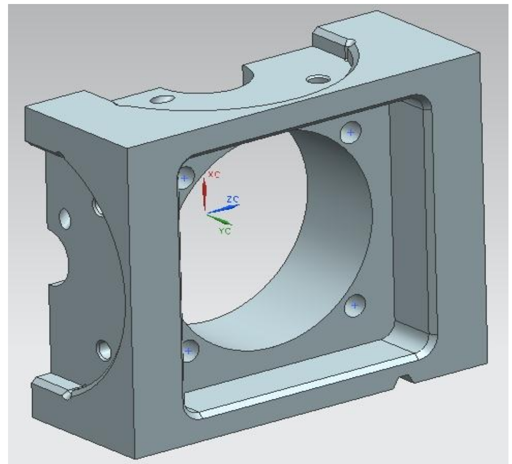


Figure 3.29 Half-cube 2 after to be machined in the cell

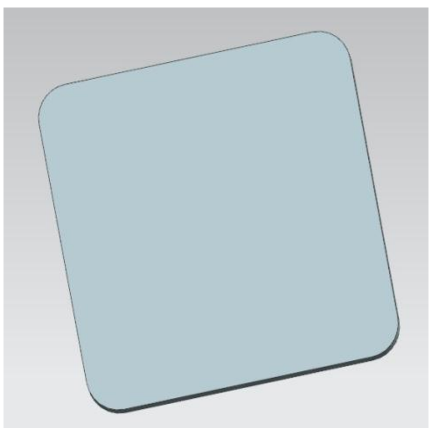


Figure 3.30 Acrylic lid before to be machined in the cell

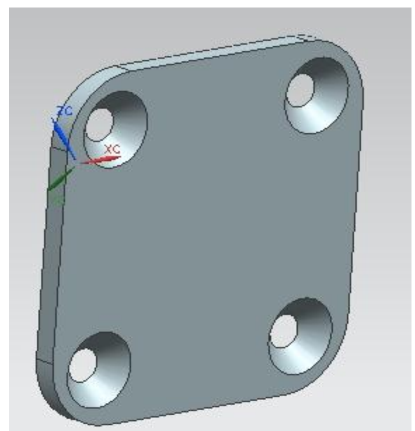


Figure 3.31 Acrylic lid after to be machined in the cell

The manufacturing times of these three parts were obtained from a simulation made in NX 8 in the manufacturing module.

There are two options for the other parts:

1) are commercials
2) are going to be pre-manufactured or manufactured by a supplier

In this case some parts will be assembled by the Robot in the automatic assembly station and other parts will be assembled by an operator in the manual station. All the parts in the Automatic Assembly station are handled by the gripper tool except the acrylic lid that is handled by the suction cup.

There are going to be four pallets in the cell that are going to contain all the parts:

1st pallet: the two half-cube and 4 Screws M4 (for the vertical chiller)

2nd pallet: the rod mechanism, holder, inertia wheel, 2 o-rings, bushing for the half-cube 1, bushing for the horizontal chiller, screw for the inertia wheel, piston and 4 screws M3 (for the horizontal chiller).

3rd pallet: Vertical and horizontal chillers.

4th pallet: pyrex cover, acrylic lid and 4 countersink Screws M4 (for the acrylic lid).

The pictures of the pallets are shown from the Figure 3.32 to the Figure 3.35:

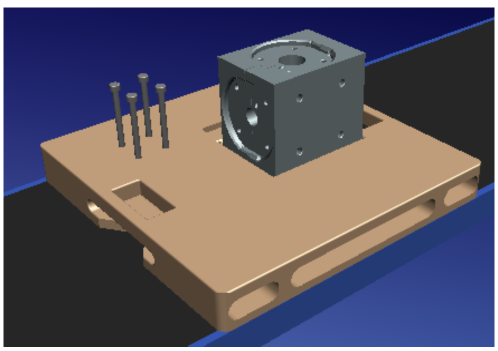


Figure 3.32 Pallet 1

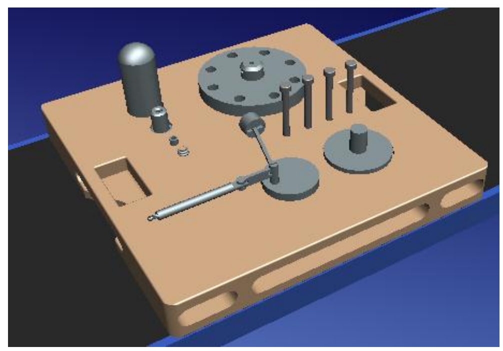


Figure 3.33 Pallet 2

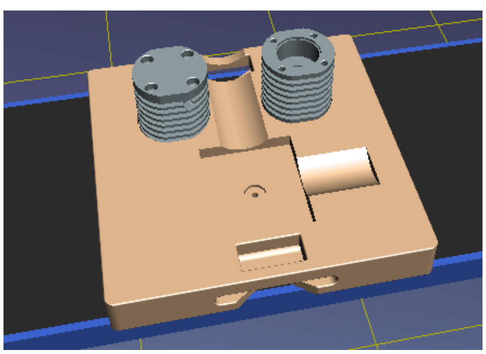


Figure 3.34 Pallet 3

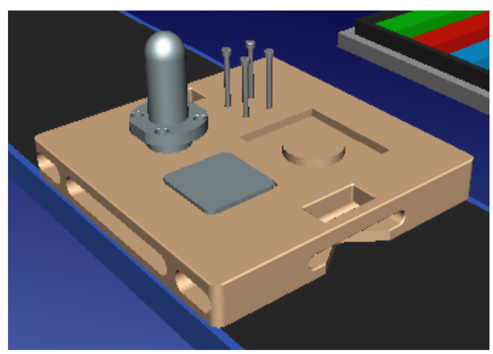


Figure 3.35 Pallet 4

Process of the production of the Stirling motor in the cell

1. The pallet 1, 3 and 4 are going to be sent to the Automatic Assembly Station
2. The pallet 2 is going to be sent to the manual station.
3. The half-cube 1 is machined at the CNC. After this, the half-cube 1 is put in the pallet 3 and the pallet 3 is sent to the manual station. In this station are going to be

assembled the rod mechanism with the half-cube 1, the holder, the bushing with half-cube 1, the other bushing with the horizontal chiller and the o-rings with the chillers.

4. The CNC continue with the machined of the half-cube 2 and after this, it is put in the pallet 4.
5. The Motoman Robot takes the pallet 1 and sends it to the manual station.
6. The Motoman Robot takes the Acrylic lid from the pallet 4 to the CNC to be machined. Then the acrylic lid is put back by the robot in the pallet 4.
7. The pallet 3 is sent to the automatic assembly station. The vertical and horizontal chillers are assembled by the robot with the half-cube 1.
8. The pallet 3 is sent to the manual station. The holder is taken out and the piston is assembled with the rod mechanism.
9. The pallet 3 is sent to the automatic assembly station. The half-cube 2 and the acrylic lid are assembled with the other parts by the robot in the pallet 3. Then the robot screws the acrylic lid to the two half-cubes. After this the robot places the pyrex cover over the piston.
10. The pallet 3 is sent to the manual station. The pyrex cover is aligned and screwed to the horizontal chiller. The inertia wheel is assembled and screwed. All this assembly is placed in the pallet 1.
11. The pallet 1 is sent to the automatic assembly station. The vertical chiller is screwed to the 2 half-cubes.
12. The final product is sent to the inspection station and then to the storage.
13. The other three pallets are sent to the storage too.

Subassembly 1: Assemble the rod mechanism, the holder, the bushing with the half-cube 1, the other bushing with the horizontal chiller and the O-rings with the two chillers.
Subassembly 2: Assemble the vertical and horizontal chillers with the half-cube 1
Subassembly 3: Assemble the piston with the rod mechanism and take out the holder.
Subassembly 4: Assemble the half-cube 2 and the acrylic lid with the other parts in the pallet 3. Screw the acrylic lid to the two half-cubes. Place the Pyrex cover over the piston.

Subassembly 5: Align the Pyrex cover and screw it to the horizontal chiller. Assemble the inertia wheel and screw it. All this assembly is placed in the pallet 1.

In the Figure 3.36 is shown the flow diagram of the Stirling motor production and in the Table 3.4 is shown a brief Graphic Production Process of the Stirling motor.

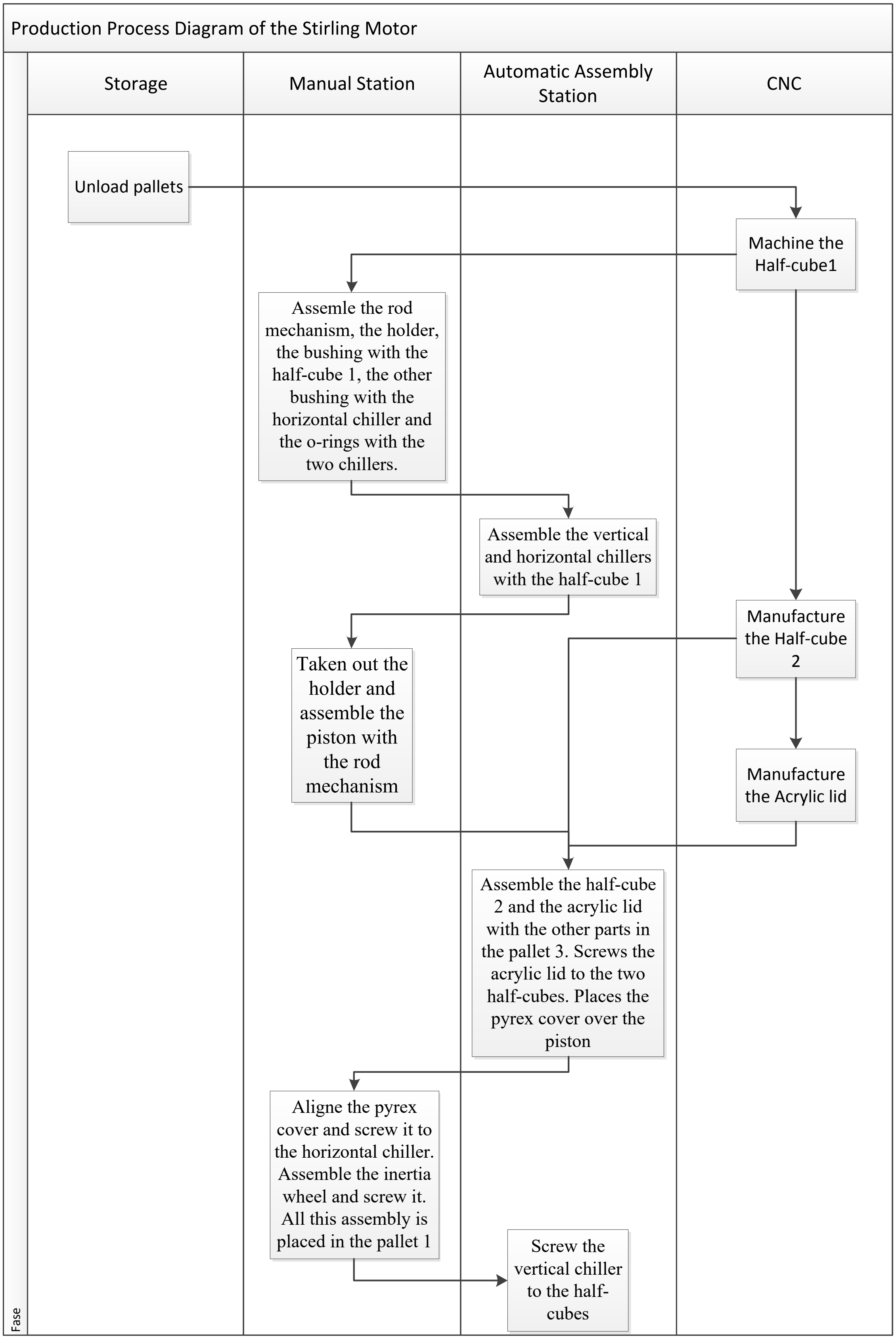
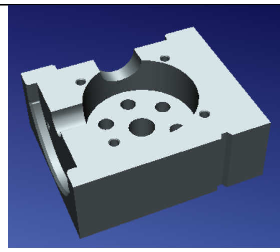
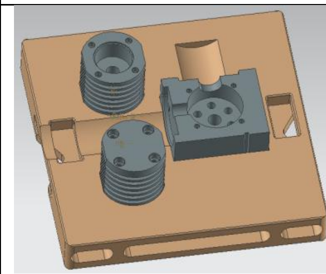
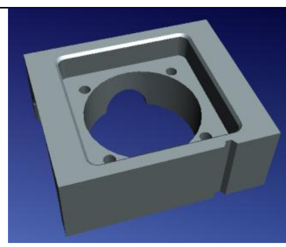
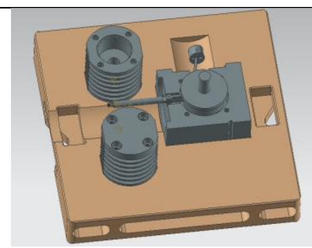
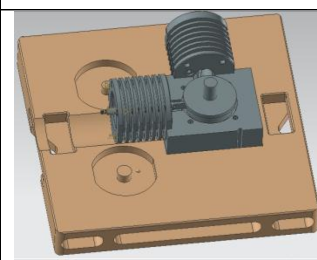
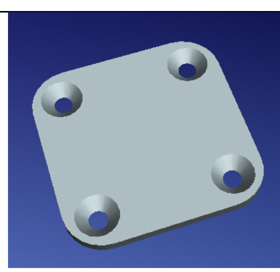
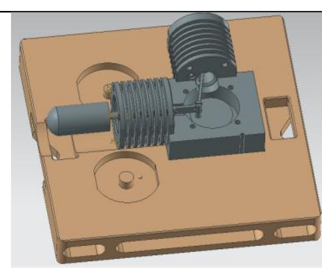
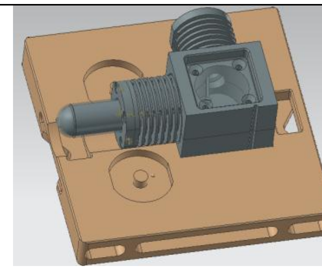
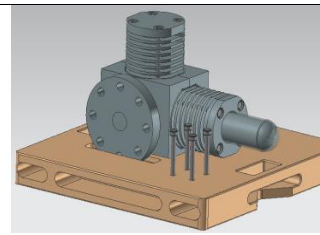
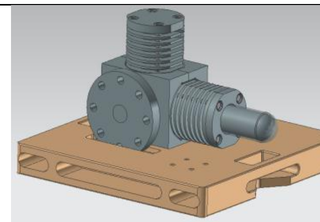


Figure 3.36 Process Diagram of the Stirling Motor

Table 3.4 Brief Graphic Production Process of the Stirling Motor

Process	CNC	Manual Station	Automatic Assembly Station
1.Machine Half-cube 1			
2. Place the Half-cube 1 in the pallet 3			
3. Machine Turbine cover and make the subassembly 1			
4. Make the subassembly 2			
5. Machine Acrylic lid and make the subassembly 3			

6. Make the subassembly 4			
7. Make the subassembly 5			
8. Screw the vertical chiller to the half-cubes			

The times of each operation of the production is shown in the Table 3.5. These times was taken observing the movements of the Motoman Robot, taking in count the velocity of the conveyor belt and taken times to different persons making the part corresponding to the manual station.

Table 3.5 Operations with their respective times for the Stirling motor

Activity	Time	symbol
Unload each pallet from the AS/RS system to the conveyor belt	20 seconds	t_u
Transport time from the beginning of the conveyor belt to the Automatic Assembly station (included the manipulation of the robot)	45 seconds	t_{c-a}
Transport time from the beginning of the conveyor belt to the manual station	50 seconds	t_{c-m}
Transport time from the Automatic Assembly station to the CNC Milling machine (time that the robot takes to bring the part from the automatic assembly station to	20 seconds	t_{a-cnc}

the CNC Milling machine)		
Transport time from the CNC milling machine to the Automatic Assembly station (time that the robot takes to bring the part from the CNC milling machine to the automatic assembly station)	20 seconds	t_{cnc-a}
Manufactured time for half-cube 1	360 seconds	t_{cm1}
Manufactured time for half-cube 2	510 seconds	t_{cm2}
Manufacture time for the Acrylic lid	150 seconds	t_{alm}
Manual assembly time to put together the rod mechanism in the half-cube 1, the holder, the bushing with half-cube 1, the other bushing with the horizontal chiller and the o-rings with the chillers.	120 seconds	t_{1ma}
Transport time from the Automatic assembly station to the conveyor belt	15 seconds	t_{a-cb}
Transport time from the Automatic assembly station to the manual station (included the manipulation of the robot).	35 seconds	t_{a-m}
Transport time from the manual station to the Automatic assembly station (included the manipulation of the robot).	55 seconds	t_{m-a}
Transport time from the Automatic assembly station to the Inspection station (included the manipulation of the robot)	30 seconds	t_{a-i}
Inspection to the final pallet	10 seconds	t_i
Transport from the inspection station to the AS/RS system (No included the manipulation of the AS/RS)	25 seconds	$t_{i-as/rs}$
Load the final product to the AS/RS system	20 seconds	t_l
Automatic assembly time to put together the two chillers with the half-cube 1.	30 seconds	t_{ach}
Time spent to taken out the holder and to assemble the piston with the rod mechanism in Pallet 3	25 seconds	t_{prm}
Time spent to assemble the half-cube 2 and the acrylic lid with the other parts by the robot in the pallet 3.	180 seconds	t_{sAl}

Also for screws the acrylic lid to the two half-cubes and to place the pyrex cover over the piston.		
The pyrex cover is aligned and screwed to the horizontal chiller. The inertia wheel is assembled and screwed. All this assembly is placed in the pallet 1	120 seconds	t_{IW}
Vertical chiller is screwed to the 2 half-cubes	150 seconds	t_{sVch}
Transport time from the manual station to the AS/RS station	15 seconds	$t_{m-as/rs}$
Transport time from the automatic assembly station to the AS/RS station (included the manipulation of the robot)	40 seconds	$t_{a-as/rs}$

First at all the Cycle Time is going to be calculated with the equation 4.3:

$$T_c = T_o + T_h \qquad (4.3)$$

$$T_c = t_u + 3t_{c-a} + t_{a-cnc} + t_{cm1} + t_{cm2} + t_{cnc-a} + t_{a-cb} + t_{a-cnc} + t_{cm} + t_{cnc-a} + t_{a-cnc} + t_{alm} + t_{cnc-a} + t_{m-a} + t_{ach} + t_{a-m} + t_{prm} + t_{m-a} + t_{sAl} + t_{a-m} + t_{IW} + t_{m-a} + t_{sVch} + t_{a-i} + t_i + t_{i-as/rs} + t_l + 2 * (t_{m-as/rs} + t_l) + t_{a-as/rs} + t_l \qquad (4.8)$$

And reducing similar terms the equation can be expressed as:

$$T_c = t_u + 3t_{c-a} + 3t_{a-cnc} + t_{cm1} + t_{cm2} + 3t_{cnc-a} + t_{a-cb} + t_{alm} + 3t_{m-a} + t_{ach} + 2t_{a-m} + t_{prm} + t_{sAl} + t_{IW} + t_{sVch} + t_{a-i} + t_i + t_{i-as/rs} + 4t_l + 2t_{m-as/rs} + t_{a-as/rs} \qquad (4.9)$$

$$T_c = 20 + 3(45) + 3(20) + 360 + 510 + 3(20) + 15 + 150 + 3(55) + 30 + 2(35) + 25 + 180 + 120 + 150 + 30 + 10 + 25 + 4(20) + 2(15) + 40 = 2265\ seconds = 37\ minutes\ and\ 45\ seconds$$

Therefore the production rate is:

$$R_p = \frac{60}{T_c(min)} \qquad (4.5)$$

$$R_p = \frac{60}{37.75} = 1.5894\ pc/hr$$

The workload for a given station is defined as the total time spent at the station per product. The calculation is shown next:

$$WL_i = \sum_j t_{ij} \qquad (4.1)$$

$$WL_{load/unload\ station} = 4t_u + 4t_l = 4(20) + 4(20) = 160\ seconds$$

$$WL_{inspection\ station} = t_i = 10\ seconds$$

$$WL_{Milling\ CNC\ station} = t_{cm1} + t_{cm2} + t_{alm} = 360 + 510 + 150 = 1020\ seconds$$

$$WL_{Automatic\ Assembly\ station} = t_{ach} + t_{sAl} + t_{sVch} = 30 + 180 + 150 = 360\ seconds$$

$$WL_{Motoman\ Robot} = t_{ach} + t_{sAl} + t_{sVch} + 6t_{cnc-a} + 12t_{a-cb}$$
$$= 30 + 180 + 150 + 6(20) + 12(15) = 660\ seconds$$

$$WL_{Manual\ station} = t_{lma} + t_{prm} + t_{IW} = 120 + 25 + 120 = 265\ seconds$$

And the utilization of each Station is:

$$U_i = \frac{WL_i}{s_i}\left(R_p{}^*\right) \qquad (4.6)$$

$$U_{Load/unload\ station} = \frac{160}{60}\left(\frac{1.5894}{60}\right) = 0.07064 * 100\% = 7.064\%$$

$$U_{inspection\ station} = \frac{10}{60}\left(\frac{1.5894}{60}\right) = 0.004415 * 100\% = 0.44415\%$$

$$U_{Milling\ CNC\ station} = \frac{1020}{60}\left(\frac{1.5894}{60}\right) = 0.45033 * 100\% = 45.033\%$$

$$U_{Automatic\ Assembly\ station} = \frac{360}{60}\left(\frac{1.5894}{60}\right) = 0.15894 * 100\% = 15.894\%$$

$$U_{Motoman\ Robot} = \frac{660}{60}\left(\frac{1.5894}{60}\right) = 0.29139 * 100\% = 29.139\%$$

$$U_{Manual\ station} = \frac{265}{60}\left(\frac{1.5894}{60}\right) = 0.11699 * 100\% = 11.699\%$$

3.2.1 Results

The production process for the Stirling motor was created and simulated obtaining approximately the same results that the obtained mathematically.

The cycle time obtained was 37 $minutes\ and$ 45 $seconds$, the production rate was 1.5894 pc/hr.

The production process of the stirling motor is longer than the Tesla Turbine because

- It has more components
- The components are more difficult to manipulate with a robot so a manual station has to be included.
- More assemblies are made with Stirling Motor.
- The machining times are longer because more material is roughed down from the pieces and because the material (Aluminium) is harder than the Tesla Turbine (nylamid).

The utilization of the stations are shown in the Figure 3.37

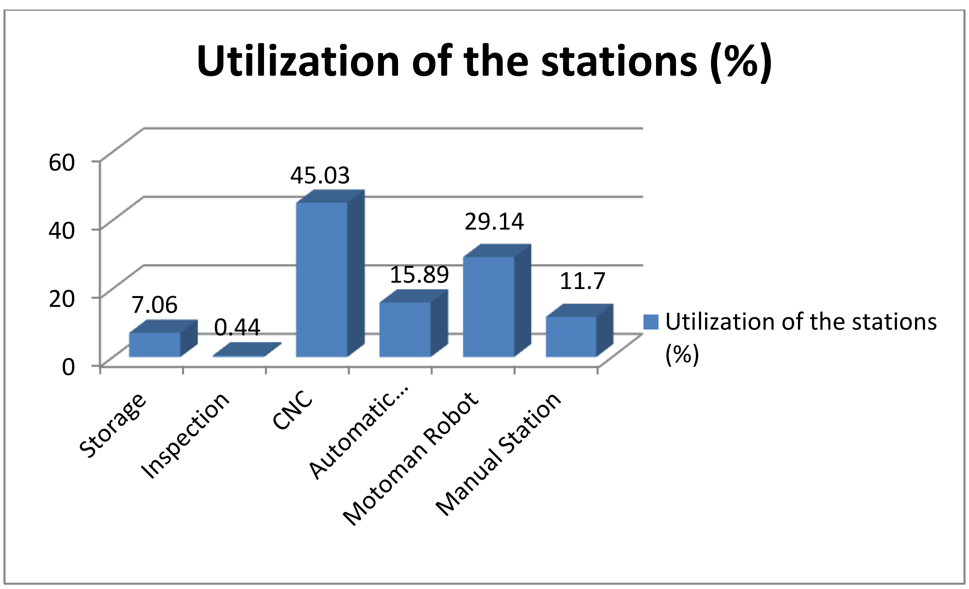


Figure 3.37 Utilization of the stations

Simulation of the production process in “Plant Simulation”

The parts for the Stirling Motor were created in the frame called “AS_RS_Storage” that simulates the AS/RS system together with the object called “StorageRobot”. The Assemblies were made in the frame called “Automatic_Assembly” that simulates the Automatic Assembly Station that is the place where the robot made the Assemblies.

The Figure 3.38 shows the configuration of the cell for the production of the Stirling motor.

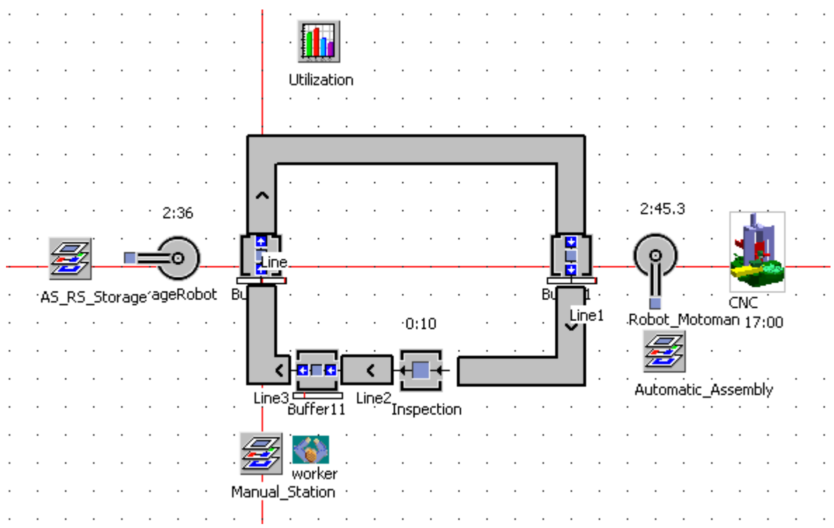


Figure 3.38 Configuration of the cell for the production of the Stirling motor

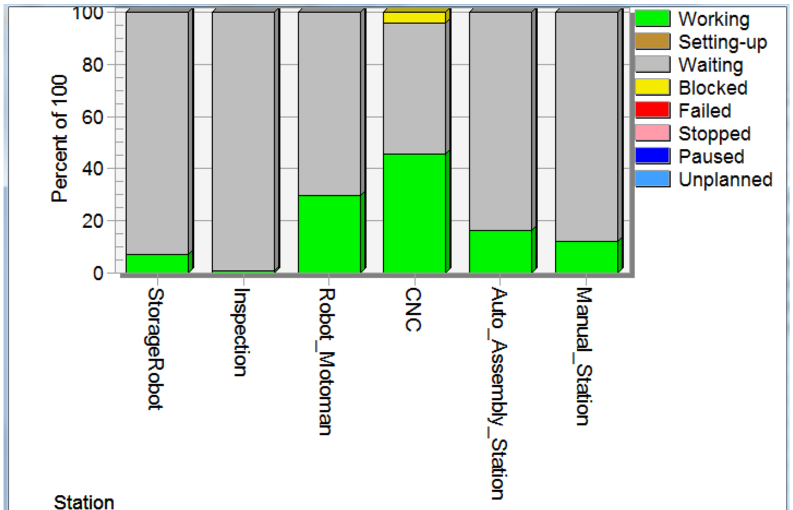
The Figure 3.39 shows the simulation time and also when each pallet comes back to the AS/RS Storage. The last pallet gets out at 37:02 approximately, so it is the Cycle Time of the production of the Stirling motor.

Simulation time: 37:20.0000

Object	Name	Mean Life Time
AS_RS_Storage.outDemo	Pallet1	34:42.0000
AS_RS_Storage.outPallet2empty	Pallet2	37:02.0000
AS_RS_Storage.outPallet3empty	Pallet3	36:22.0000
AS_RS_Storage.outPallet4empty	Pallet4	35:42.0000

Figure 3.39 Simulation time for the Stirling Motor

The Figure 3.40 shows the utilization of the stations in the cell. The yellow part of the CNC statistics bar means the time in percentage that the CNC is waiting for the Motoman Robot to pick up a machined part from the CNC.



Station	StorageRobot	Inspection	Robot_Motoman	CNC	Auto_Assembly_Station	Manual_Station
Working	6.96%	0.45%	29.48%	45.54%	16.07%	11.83%
Setting-up	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Waiting	93.04%	99.55%	70.52%	50.57%	83.93%	88.17%
Blocked	0.00%	0.00%	0.00%	3.89%	0.00%	0.00%
Failed	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Stopped	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Paused	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Unplanned	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Figure 3.40 Utilization of the stations

4 Conclusions

For the Tesla Turbine, making two processes in parallel: machining the turbine base and turbine cover while the first assembly (assemble the shaft with the miniCDs, the washers and the nut) is made, reduces 2 minutes and 30 seconds the cycle time of the production. The reduction of the Cycle time in percentage was 13.21%. Therefore the objective of improve the production rate of the Tesla Turbine in the RMS was reached. Also this process was simulated obtaining approximately the same results that the obtained mathematically.

The production process of a Stirling Motor was created using the same configuration that was used with the Tesla Turbine and the cycle time obtained was 37 minutes and 45 seconds approximately. Also this process was simulated obtaining approximately the same results that the obtained mathematically.

The following results were achieved in the development of this thesis:

- Evaluation and improvement of the production process of a Tesla Turbine in a RMS.
- Development of the production process of a Stirling motor in the RMS using the same configuration that was used with the Tesla Turbine only adding a manual station. Evaluation of the production process was made.
- Simulation of the new production process of the Tesla turbine and Stirling Motor.

4.1 Future research

- Manufacture the Stirling motor in the RMS with the production process proposed.
- Design others production process and configurations of the cell for the Stirling motor to improve the production rate.
- It is necessary to develop the software that let the reconfiguration between the first product "Tesla Turbina" and the second product "Stirling motor".
- Validate the methodology to evaluate the level of reconfigurability (presented in the Appendix) changing from one configuration to another. Measure the time of

reconfiguration between the Tesla Turbine and Stirling Motor and apply the methodology. Add other factors to the methodolgy that could affect the reconfigurability of the cell.

5 References

[1] N.P. Suh, "Axiomatic design theory for systems," *Res. Eng. Des.*, vol. 10, pp. 189-209, 1998.

[2] D.S. Cochran, F.J. Arinez, J.W. Duda, and J. Linck, "A decomposition approach for manufacturing system design.," *Journal of Manufacturing System*, vol. 20, no. 6, pp. 371-389, 2001,2002.

[3] HA ElMaraghy, "Flexible Manufacturing systems 91-512 class notes," Industrial and manufacturing systems engineering department, University of Windsor, Ontario, 2000.

[4] HA ElMaraghy, "Flexible and reconfigurable manufacturing systems," in *3rd Conference on Reconfigurable Manufacturing*, Ann Arbor, 2005.

[5] A. Gunasekaran and Y. Yusuf, "Agile manufacturing: A taxonomy of strategic and technological imperatives," *International Journal of Production Research*, vol. 40, no. 6, pp. 1357-1385, 2002.

[6] S. Jain, "Virtual factory framework: a key enabler for agile manufacturing," *Emerging Technologies and Factory Automation*, vol. 1, pp. 247-258, 1995.

[7] J. Aitken and M. Christopher, "Understanding, Implementing and Exploiting Agility and Leanness," *International Journal of Logistics*, vol. 5, no. 1, pp. 59-74.

[8] Y Koren and A. G. Ulsoy, "Vision, Principles and Impact of Reconfigurable Manufacturing Systems," *Powertrain International*, pp. 14-21, 2002.

[9] L. M. Sánchez and Nagi Rakesh, "A review of agile manufacturing systems," *International Journal of Production Research*, vol. 39, no. 16, pp. 3561-3600, 2001.

[10] D. Parrish, *Flexible Manufacturing*. Cambridge U.K: Butterworth-Heinemmann, 1990.

[11] H. Temperlmeier and H. Kuhn, *Flexible Manufacturing Systems*.: John Wiley & Sons, Inc., 1993.

[12] M. Kaighobadi and K. Venkatesh, "Flexible Manufacturing System: an overview," *International Journal of Operations & Production Management*, vol. 14, no. 4, pp. 26-49, 1994.

[13] R Narain and R.C. Yadav, "Productivity gains from flexible manufacturing, experiences from India," *International Journal of Productivity and Performance Management*, vol. 53, no. 2, pp. 109-128, 2004.

[14] S. Irani, *Handbook of cellular manufacturing systems*. New York: Wiley, 1999.

[15] Y. Koren et al., "Reconfigurable Manufacturing Systems," *Annals of CIRP*, vol. 48, no. 2, pp. 527-540, 1999.

[16] R. Cardinall, "Flexible manufacturing systems: a primer on enhancing productivity while controlling cost.," *Logistics Information Management*, vol. 8, no. 6, pp. 38-42, 1995.

[17] J.A. Rehg and H. W. Kraebber, *Computer-Integrated Manufacturing*.: Prentice Hall, 2001.

[18] C. Dinçer and B. Deler, "On the distribution of throughput of transfer lines," *Journal of the Operational Research Society*, vol. 51, no. 10, pp. 1170-1178, 2000.

[19] F.F. de Lamotte, P. Berruet, and J.L. Philippe, "Evaluation of Reconfigurable Manufacturing Systems configurations using tolerance criteria," *IEEE Industrial Electronics, IECON 2006- 32nd Annual Conference on*, pp. 3715-3720, 2006.

[20] Kuo Chung-Hsien, "Resource allocation and performance evaluation of the reconfigurable manufacturing systems," *Systems, Man, and Cybernetics*, vol. 4, pp. 2451-2456, 2001.

[21] Honglin Zhao, "Research on a simulation system for process capacity of Reconfigurable Manufacturing Systems," *Technology and Innovation Conference*, pp. 173-177, 2006.

[22] Y. Koren, "What are the differences between FMS & RMS.," in *3rd Conference on Reconfigurable Manufacturing*, Ann Arbor, May 2005.

[23] Z. M. Bi, S.Y. T. Lang, W. Shen, and L. Wang, "Reconfigurable Manufacturing Systems: the state of art," *International Journal of Production Research*, vol. 46, no. 4, pp. 967-992, 2008.

[24] Mikell P. Groover, *Automation, Production Systems, and Computer-Integrated Manufacturing*. Upper Saddle River: Prentice Hall, 2008.

[25] Frederick Taylor, *The Principles of Scientific Management*. New York: Norton Library, 1911.

[26] (2009) Mass Production. [Online]. http://www.wisegeek.com/what-is-massproduction.htm

[27] (2009) Lean manufacturing. [Online]. http://www.wisegeek.com/what-is-leanmanufacturing.htm

[28] (2005) SiliconFarEast. [Online]. http://www.siliconfareast.com/cellular-manufacturing.htm

[29] (2009) Flexible Manufacturing Systems. [Online]. http://www.allbusiness.com/glossaries/flexible-manufacturing-systemfms/

[30] R.M. Setchi and N. Lagos, "Reconfigurability and REconfigurable Manufacturing Systems-State-of-art Review," in *IEEE International Conference*, Berlin, Germany, 2006, pp. 529-535.

[31] M.G. Mehrabi, A.G Ulsoy, Y. Koren, and P. Heytler, "Trends and perspectives in flexible and reconfigurable manufacturing systems," *Journal of Intelligent Manufacturing*, vol. 13, no. 2, pp. 135-146, 2002.

[32] Z. Xiaobo, W. Jiancai, and L. Zhenbi, "A stochastic model of a reconfigurable manufacturing sytem," *Intelligent Journal of Production Research*, vol. 38, no. 10, pp. 2273-2285, July,2000.

[33] M.G. Mehrabi, A. G. Ulsoy, and Y. Koren, "Reconfigurable manufacturing systems: key to future manufacturing," *Journal of Intelligent Manufacturing*, no. 11, pp. 403-419, 2000.

[34] Business Dictionary. [Online]. http://www.businessdictionary.com/definition/process.html#ixzz2DS8Sr6W0

Appendix

Metodology to evaluate the reconfigurability of a cell

The cell will be 100% reconfigurable if the conveyor belts can be moved from one place to another until reach the configuration desired of the cell in a short time. After changing the configuration, the next process starts sending the order from the control station. Also the cell has to be able to manufacture all the products (except the commercial parts like screws and so on). If there is any product that cannot be manufactured maybe for its difficult geometry, so the cell is not 100% reconfigurable.

Also the time of reconfiguration cannot be taken longer than the suggested time of reconfiguration.

Number of stations	4	5	6	7	8	9
suggested time of reconfiguration (min)	15	18	21	24	27	30

The general formula would be the next:

$$Suggested\ time\ of\ reconfiguration(x) = 3(x-4)+15$$

where x is the number of stations in the cell. For a number of 4 stations or less the time suggested is 15 minutes. The time is given in minutes.

If the reconfiguration takes longer than the suggested time of reconfiguration the level of reconfiguration decrease according to the next formula:

$$P = 2 * (t_r - t_{sr}) \quad if \;\; t_r \geq t_{sr}$$
$$P = 0 \quad if \;\; t_{sr} > t_r$$

Where:

P: penalty for taking longer than the suggested time of reconfiguration. It is expressed in percentage.

t_r : is the real time of reconfiguration

t_{sr} :is the suggested time of reconfiguration.

Another key factor of reconfigurability is if the cell can manufacture all the new parts for the next product:

$$P_{MP} = \frac{N_M}{TN}$$

where:

P_{MP} = Percentage of manufactured parts

N_M = Number of parts of the new product than can be manufactured in the cell

TN = Total number of parts of the new product

So the total percentage of reconfigurability is going to be:

$$Reconfigurability(\%) = P_{MP} - P$$