Università di Pisa

Dipartimento di Ingegneria Civile e Industriale

Corso di Laurea in Ingegneria Meccanica

Tesi di Laurea Magistrale

A Comparative Cost Analysis of Flexible and Evolvable Automatic Assembly Systems

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Anno Accademico 2012/2013

Volli, e volli sempre, e fortissimamente volli

— Vittorio Alfieri

Ai miei genitori

Abstract

The objective of this work was the formulation of a cost model able to provide an evaluation of the economical effectiveness of an Evolvable Production System (EPS) compared to the Flexible Manufacturing System (FMS) within assembly process. Preliminary essential work was the literature research on cost models, which confirmed the lack of economical considerations about evolvable paradigm.

Two are the main contributions: the first is the definition of the cost model for EPS and FMS throughout multiple product life cycles. After the definition of the model, it has been proposed a parametrical comparative analysis between the two systems within different productive scenarios. The comparative cost analysis was simulated through the implementation of the model on MATLAB.

This work takes place within the research about Evolvable Production Systems carried out at the Royal Institute of Technology in Stockholm.

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Chapter 1

Introduction

1.1 Current Praxis in assembly automation

Assembly is the key-stone of a manufacturing process.
It is not just the connection of all product parts: it is the last step of the production stream after design, engineering and manufacturing.
To assembly together many parts a thorough design process must be done. Differently from the other manufacturing processes, assembly was involved quite late in the automation technology. This can be explained as follows: whilst requirements of strength and precision demanded by manufacturing operations like turning or milling can not being performed by human operators, they can execute assembly quite easily.

Depending on production requirements, one can choose among different solutions of manufacturing processes. Traditional automation is based on hardware elements called equipment connected to a Programmable Logic Controller (hence PLC). The process is implemented by a part program which is basically a quite rigid logic sequence of instructions. Once the program is fixed, in case of changes (e.g., increasing productive demand, new processes)is necessary to restore all the control system and all the electro-mechanical connections among the workstations. Thus robotics assembly system are not as *flexible* as they are supposed to be.

It is useful to give a description of the current business approach, as portrayed in fig.1.1:.
The three main stakeholders involved in the common approach to design and develop an automated production system are:

- The Company that needs the system to produce the product;
- The Module Supplier (MS) that designs and supplies the fundamental building block of the system;
- The System Integrator (SI) that provides the technical capability of developing suitable solutions.

In the common situation the Company after having realized the full design of a new product, contacts the SI asking for an automatic solution to manufacturing. The SI is responsible for the definition of the system requirements. So, based on its experience, it can decide which approach is most promising in terms of implied system cost. Considering the already available resources the SI buys new hardware from several MSs and it proceeds with the necessary physical and logical integration. It is possible then that the common purposes push the players to join the efforts. SI might ask MS for a module with customized layout or it can suggest the Company small adjustments on the product design to simplify some manufacturing task.
As a result of this approach product design and production system design are two phases that denote a very weak or non-existent link between the three stake-holders.

1.2 Alternatives to traditional systems

In an era of global competition, markets which change really fast and mass customization, where every customer receives a personalized product, a

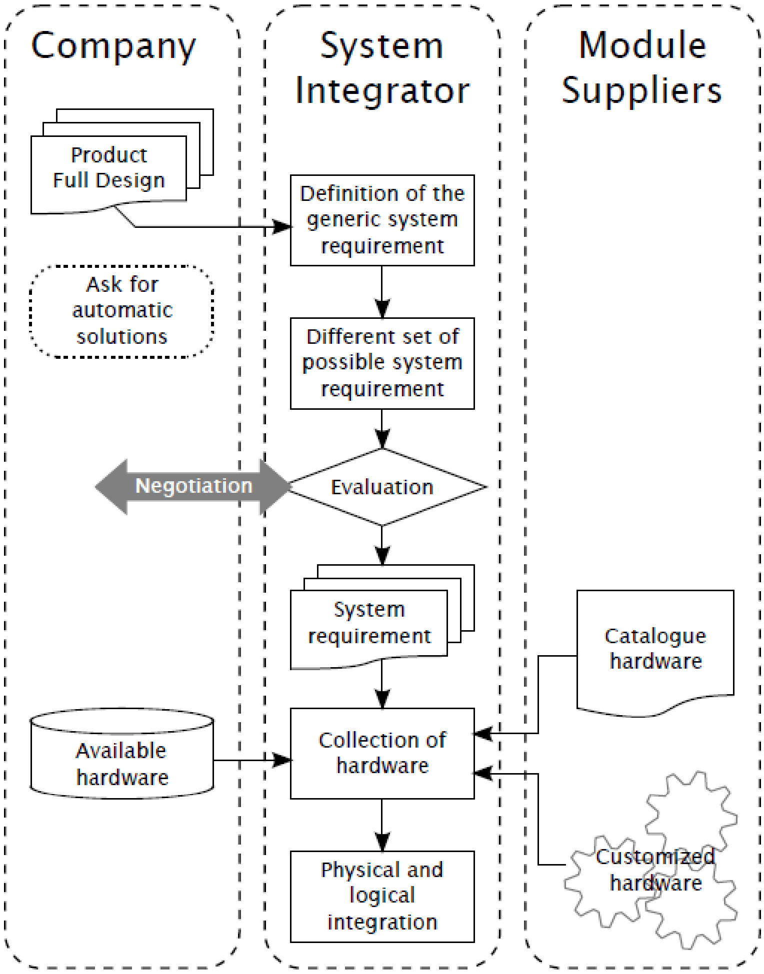

Figure 1.1: Current practice in production system development [28]

manufacturing company has to be flexible to satisfy customers demand and survive on the market of labor. Therefore the competition is more and more based on the ability to quickly adapt to change and to account for market evolution. Henceforth the technological solution must adapt dynamically and continuously to the context at as low cost as possible.

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Moreover another relevant fact is the cheap cost of labour in developing

countries. Recent studies quantify European outsourcing outside Europe at 21% of total assembly activities and had forecasted a rise to over 40% by 2007. Since 2007 the economic downturn and established outsourcing procedures have worsened the case. European enterprises are countering this situation automating their processes but as mentioned before the way automation is achieved today is expensive and therefore it is convenient only for both large and high value added productions. These costs cannot be sustained by the small and medium enterprises so they do not have the financial strength to afford automation. Those enterprises are the backbone of European economy; more than 120 million people are directly employed in this sector hence their needs need to be highlighted. The need for both agile and sustainable automatic solutions is now fundamental for the survival of European manufacturing industry. [28]
In order to cope with the requirement described above, a large number of research efforts is being carried out. Among them the IDEAS project, which is detailed in the next section, is the framework of the work presented in this thesis.

1.3 The IDEAS Project

IDEAS is an acronym standing for Instantly Deployable Evolvable Assembly Systems. The IDEAS project involves several European institutions are involved in the IDEAS Project. Evolvable Production Systems (EPS) Group from Kungliga Tekniska Högskolan is currently working in a consortium of other European Universities, research institutions and Companies. The aim is to achieve the needed shift of paradigm.
The target of this European network is a production system that is not only easily mechanically reconfigurable but also and especially that shows autonomy in tasks like:

- Integrating new productive modules;

- Changing processes;
- Monitoring and diagnosis;
- Communication with the Enterprise Resource Planning (ERP) systems;
- Internal material flow management

In other words the control system must be able to hide the underlying complexity of the logical integration of the system itself and with the other pertinent entities in the company. Moreover this kind of system forces the main stakeholders involved in the to change the way they approach their activities, promoting a 'cooperation' policy, aiming a common purpose. It is proposed a new production paradigm able to cope with new requirements of markets, the Evolvable paradigm. Therfore Evolvable Production Systems(EPS) have been introduced in order to face the growing mass customization requirements.

1.4 Synopsis of this work

The work done so far on EPS systems has been mostly based on the development of the informatics structures able to run such a complex system as Multi Agent system is. Another object of research is the evaluation of the economical impact of such system within industrial reality: this is purpose of this work.
In hereby study the author focused on the effectiveness of such system from the cost view point. Therefore a cost model has been developed in order to probe the potentials of the new system if compared with traditional flexible systems.

Hence here is listed a brief list of the thesis structure:

Chapter 2 It is presented an interdisciplinary literature review. First of all, traditional flexible assembly system are presented. Secondly evolvable paradigm is introduced and a comparison of the two approaches is discussed. After that there is a review of cost models literature.

Chapter 3 It is defined the problem to study. This chapter describes the research methodology and it is discussed the domain of this work

Chapter 4 There is a formulation of the cost model for the comparison analysis, and the boundaries of the model are delineated.

Chapter 5 The comparative cost analysis between the two system has been carried out, with a numerical illustrative example.

Chapter 6 Conclusions and future developments are listed, along with some critical observations.

Chapter 2

BackGround

In this chapter the automatic assembly systems which will be object of this work are introduced: flexible assembly system and evolvable production systems. Afterward there are basics of costing methods used for building the model and the comparative analysis.

2.1 Flexible Manufacturing System

2.1.1 Flexibility in Automation

In the context of assembly, flexibility is the ability to adapt an assembly system quickly and with little effort to changed influencing factors. With regard to flexibility, technical changes are limited at the design phase of the system by defined flexibility corridors (Abele [14]). Therefore a change in the number of workstations in an assembly system, for example, can be represented to a pre-defined extent within these corridors. Conversely changeability, means that the system can potentially implement possible changes beyond the flexibility corridor defined during design phase. (fig. 2.1). So, when planning changeable assembly systems, there is not any explicit limits set. It is important to underline that flexibility and changeability are not independent each other. Changeability is effective if new requirements of production system are over the flexibility corridor boundaries. The

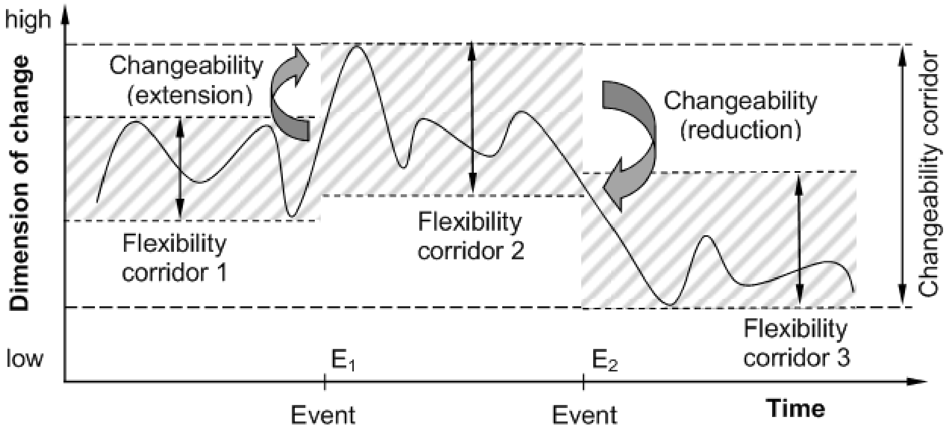

Figure 2.1: changeability and flexibility [10]

influencing factors that lead to turbulence in the assembly system come from a number of external sources **??**. or from the production system itself. They affect assembly via a certain number of channels. The influencing factors include, among others:

- products and product variants
- costs
- time
- number of units
- quality
- elements of the assembly system (process technologies, system technology, tools, etc.)

There is the need to satisfy all those requirements, flexibility can be reached by many different approaches for the description and measurement of manufacturing flexibility, a common definition of manufacturing flexibility and its various types a unique definition of flexibility is not available. Flexibility can be achieved in different ways. The taxonomy of flexibility types established by Browne [16] has formed the foundation of most subsequent research into measuring manufacturing flexibility. In their review, Sethi and Sethi ([13]) identify over 50 terms for various flexibility types, although generally the basis of all work has been that of Browne [16]. A list of flexibility type definitions is reported below.

Machine flexibility 'refers to the various types of operations that the machine can perform without requiring prohibitive effort in switching from one operation to another' ([13])

Process flexibility is the ability to change between the production of different products with the least delay.

Product flexibility is the ability to change the mix of products in current production, also known as mix-change flexibility ([17]).

Routing flexibility is the ability to vary the path a part may take through the manufacturing system.

Volume flexibility is the ability to operate with different production volumes.

Expansion flexibility is the ability to expand the capacity of the system as needed, easily and modularly.

Operation flexibility is the ability to interchange the sequence of manufacturing operations for a given part.

Production flexibility is the universe of part types that the manufacturing system is able to make. This flexibility type requires the attainment of the previous seven flexibility types.

This classification supports better understanding of various types of flexibility although some of them are interconnected.It should be noted that the expansion flexibility is In particular the limitation of process flexibility is one of the triggers of the research for new paradigms which are able to replace the present resources without much effort. One of them is the evolvable paradigm which will be presented in the next paragraphs.

Bodine [30] identifies three levels of flexibility within an assembly system:

Level 1, Change-over flexibility The ability for an assembly system to handle variations among a family of products. Only a minimal of change-over is required as the product variations are known and are planned for when designing the system.

Level 2, Product flexibility The ability to accommodate future product changes. This may require adding or revisiting of tooling and product design. Even though the actual product changes are unforeseen, it is often possible to identify the affected areas and types of changes.

Level 3, System re-use flexibility The ability to produce a completely new product by (cost-effectively) re-tooling or re-engineering of the assembly system. This is in many respects the most challenging form of flexibility and it is tightly linked to the degree of modularity of the system.

2.1.2 Description of the FMS system

As depicted in fig. 2.2 flexible automation is usually thought based on robots. In general, however, flexible automation may be defined as any automation which is able to accomplish different tasks. Those machines are characterized by different abilities like move with controllable degrees of freedom, forces applied. Robots can change tools and accomplish more than one task. Much of their flexibility is based on computer control. Control logic is based on serial programming. All the equipment is controlled by a Programmable Logic Controller (hence PLC). The logic structure is a list of logical propositions (i.e. if/then, or/and).

This means that if one wants to change one process in the work-flow, it need to modify all the sequence of commands. Indeed with a centralized architecture, every equipment deals with the PLC. There may be some setup time penalties every time the assembly systems needs to be adapted to the considered production. Usually FMS systems is built to deal with a family of products. The system design is the result of an accurate study of the characteristics of the products. The robot are multi-purpose module with high effectiveness. Whenever the assembly systems needs to be adapted to the different production it needs to be re-engineered. The logical and mechanical integration are adapted to the specific family of products. Therefore even though the system is conceptually reusable for other production, very often it needs to be remade almost from scratch. The time needed for the assembly line to be adapted to new productions makes the system slow and not so flexible. This happen every time the requirements come out of the boundaries fixed a priori during the system design phase. Moreover after having built the line with all the mechanical, electrical and logical connection the system needs to be tested.

As stated by Shewchuk [34] there are two drawbacks to this approach, however. The first is that the possible states are fixed in advance, limiting the ability of the system to cope with unanticipated changes. The second is that though flexibility is designed in and paid for in advance, it is only required at very infrequent intervals in this environment. The vast majority of the time, flexibility is of no value: the objective is to maximize throughput. Thus, the use of flexibility as a mechanism for coping in this environment is not cost-effective.

2.2 Evolvable Production Systems

The need to overcome all the discussed drawbacks of previous approaches, pushes the research towards the idea to put the focus on the processes and on the modularity, instead of the product and the flexibility.

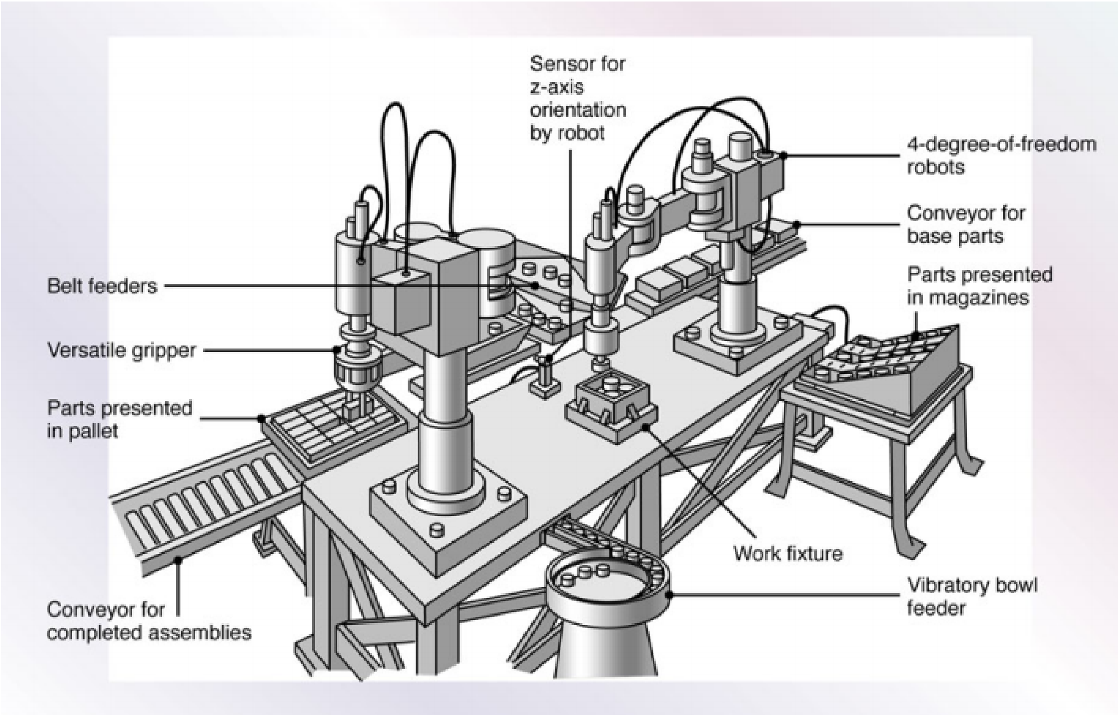

Figure 2.2: Flexible assembly line

2.2.1 Description of the system

Basically *An evolvable system is a system that evolves over time to suit product and/or production requirements in order to achieve optimal fitness along its lifetime. It is highly sustainable, re-configurable and agile since it is composed by standardized interoperable modules that can be easily exchanged.*[8] In evolvable systems, assembly is divided into executable sub-processes which are tightly linked to the product, are skill-oriented rather than service-oriented.

The first feature of an EPS is the modularity. Modularity production present some advantages:

- standard diversity by using different combination of standard components
- it resists obsolescence
- it reduces and simplify redesign

- it enables new design to be realized using existing modules
- it reduce costs
- it eases maintenance

Modularity enables the chance to quickly reconfigure production in order to reach short- and long term- objectives. EPS paradigm aims to agility and sustainability. Therefore it is a fundamental need to carry out a dynamic connection between design of the product and design of the production system. The production is described by means the processes which compose it. Each module is *task-specific* and *process-oriented*. To each module is related a specific atomic skill.

Each task can be split in a list of operations which encompass many basic activities.

An EPS module must be able to communicate with other modules and to be self-conscious of its skills. Every module has an embedded controller so . It is essential for the modules being equipped with standard mechanical and logical interfaces. Thus a fast and easy construction of the system is possible, whenever it is needed.

The Evolvable paradigm aims to be a self-optimising assembly systems, allowing short-term adaptations to current conditions and objectives to be made with the least of planning, reconfiguration and change-over effort. In this aspect self-optimisation is meant as the ability of a system to continuously analyse of the current situation, to derive system objectives based on that analysis and therefore to autonomously adapt the system.

2.2.2 Architecture of EPS system

In order to understand EPS it is important to provide an overview of the EPS structure.
As depicted in fig. 2.3. the fundamental block of the system is the Multi Agent System, which is the control system. Multi Agent System manages

Mechatronic Agents.

A mechatronic agent is an hybrid hardware/software entity and it is the result as a combination of the three elements listed[8]: *Agent* which is a modular piece of software which can accomplish some predefined; Skill that a conceptual resources about abilities that can be performed; *Hardware* is the physical embodiment of an agent which has certain skills.

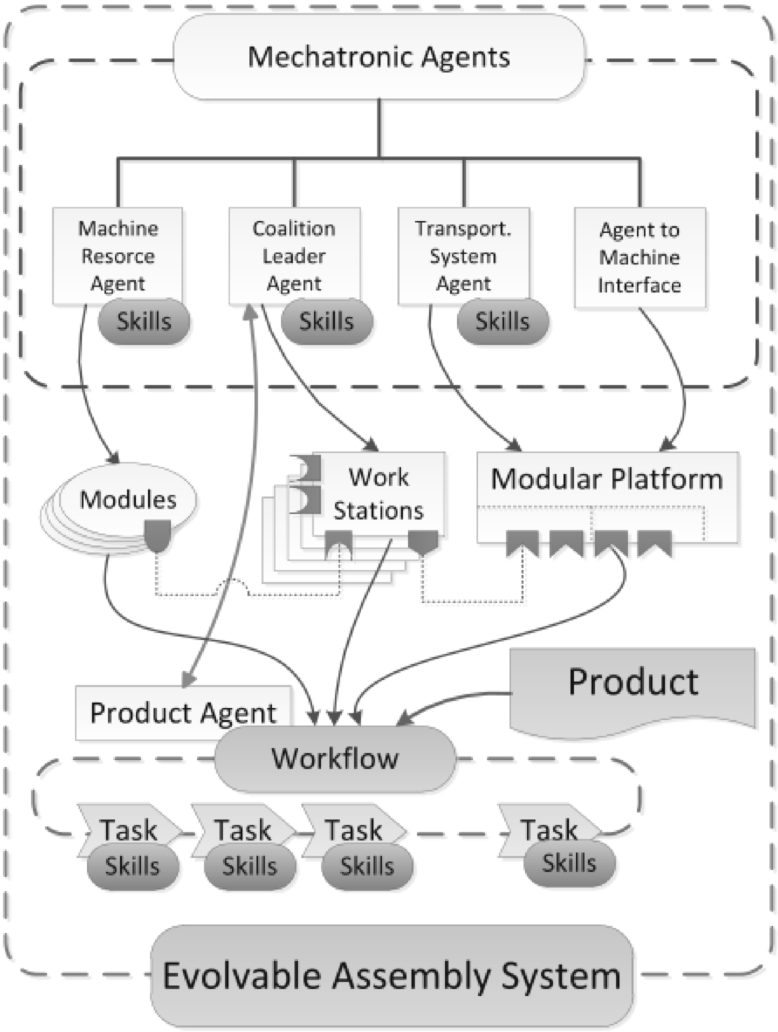

Figure 2.3: Overview of EPS structure [27]

in fig.2.3 it possible to have a look at the six basic elements for an EPS system[27]:

Multi Agent System : Modular block of software distributed in accordance with specific system requirements. It is the control system that connects all the *agents* among them. It manages and organizes the agents , which are intelligent entities, in order to accomplish required tasks.

Skill : Basic entity of the EPS paradigm. Skills carry information of the abilities of modular block of a multi-agent system. Skills define the process capabilities offered by the agents to complete the required assembly process steps. Skill capabilities will be used to select and configure a new or re-configure assembly system.

Workflow : it is the construct which encompass all the skills. Workflow is built up by analyzing the processes required to produce a particular product. All the processes required by a particular production included and sequenced. Therefore one can see to workflow as a link between product features and processes to accomplish them.

Modular Platform : Hardware element which physically connects all the blocks at workstation level. It is composed by the repetition of standard units, each of them has: interfaces for other platforms, standard interfaces

Workstation : It is a particular area in the system one or more tasks are executed. From the hardware point of view it is a collection of one or a more modules. It is governed by an agent based on processes designed by the user.

Module : It is the hardware which embodies an agent. It materially performs a task depending on the skill related with the module itself. Module, the basic blocks of a workstation, can be joint or withdrawn at at any need. System can take over also part of engineering by facilitating or even taking over part of the question of how to arrange the assembly facilities [20].

An example of EPS assessment is portrayed in fig. 2.4. In particular one can see workstations connected with the modular platform.

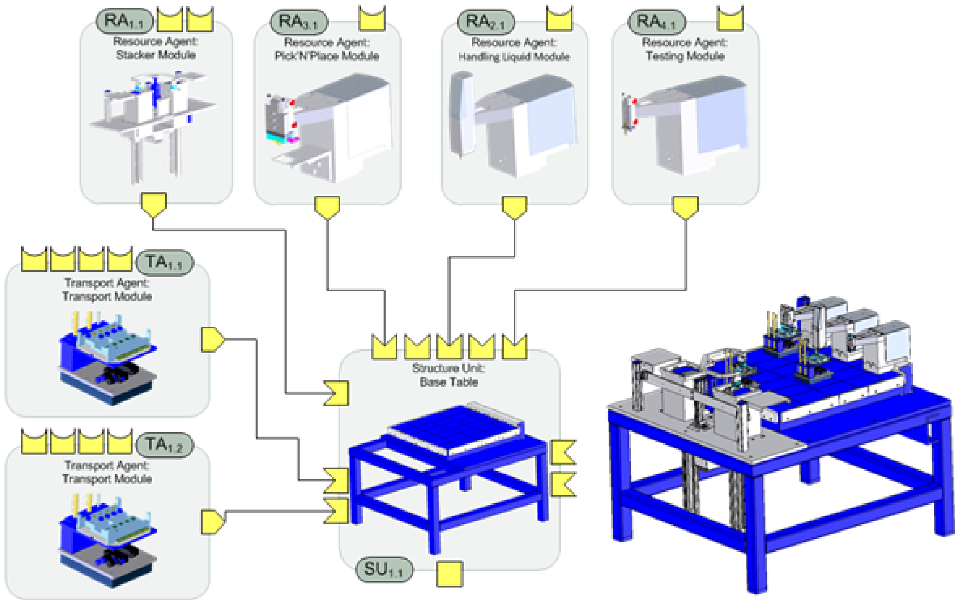

Figure 2.4: An example of EPS system

2.2.3 Classification of elements

It is possible to classify EPS elements in three groups according with the context and the dynamics [27].

- **Product-oriented elements**. This category contains all the objects that are specific for every product to be processed in the assembly line. Basically there are some elements that are specific for every product. Once the production has finished, therefore, these elements are usually not reusable. A clear instance of such elements are the specific fixtures, grippers, feeding equipment and all the other tool. Consequently during the transition from a productive cycle to the next, the product specific-elements need to be rebuilt from scratch. This will be depicted In EPS domain the process is defined as a composition of skills. The workflow that portrays the sequence of operation to accomplish to get the production process done.

- **Process oriented elements**. In EPS domain, a process, namely an assembly task, is obtained through a composition of basic skills, which are process-oriented items. The workflow changes a product into a sequence of processes. Each processes is carried out by a specific workstation. In the evolvable domain, like in flexible systems, workstations accomplish parametric process. Thus reprogramming makes possible to set the parameters of the processes in order to use the process in a similar production. the workstation can be reused in similar processes.

- **General purpose elements.** All the elements which can be used in any production system are included in this cluster. For instance Multi-Agent system, like as any other operative system for generic computational units, is a general purpose element. The atomic skill is also a general purpose element.

2.3 Lifecycle of an assembly system

It is fundamental to introduce the concept of product lifecycle and consequently the assembly system's lifecycle. In fig 2.6 it is portrayed the standard simplified lifecycle for a product.[4] which is the representation of the productive volume in function of time. According to the slopes of the curve, in the picture one can detect 4 different phases:

1. Development

2. Growth

3. Maturity

4. Decline

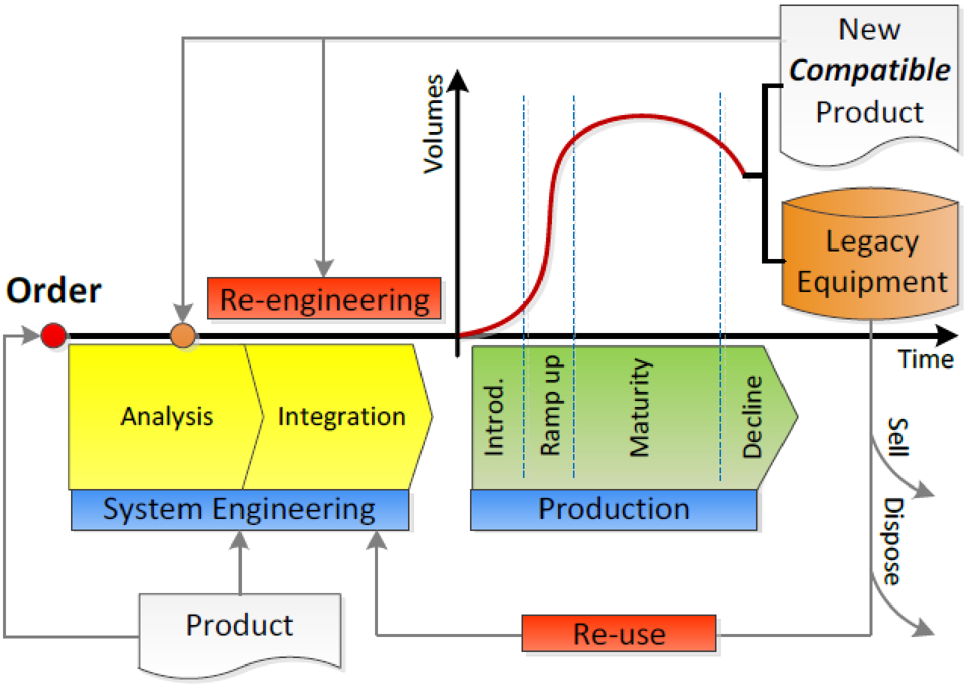

Figure 2.5: Life cycle of an automatic assembly system [27]

It is a quantification of the units sold or demanded over a product's lifetime. Product lifecycle is often used as a measure of the time a product spends in the market before becoming obsolete. The first definition is more precise because in its typical graphical representation it appears like a function of both demand and time (fig. 2.6). [33] In this work, the first definition is considered more appropriated and it is adopted referring to product life cycle. It is important to point out what happen after the production phase come to an end. There are mainly two opportunities [27]:

- The system is still able to serve the firm in new productions after re-engineering. This phase can be either simple and quite fast or complex and long. The first happen when small adjustment are required, the latter is the case when the engineering involve partial rebuilt of the line and a large redefinition of the control logic: efforts can be just like the ones to rebuilt the system from scratch.
- Re-engineering of the system is not possible or not convenient. Then

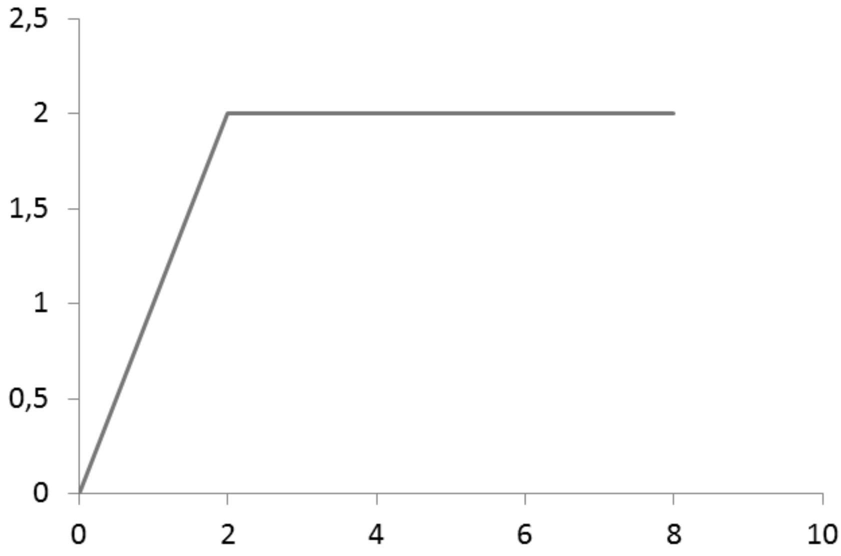

Figure 2.6: Traditional Product life cycle curve

the system must be dismantled. Usually some pieces of equipment are still valid for being re-used in other productions inside the company.

Since a production system's life is longer than a product or family product life, very often during If a production system is subject to process changes reengineering is a indispensable.

In fig. 2.7 are portrayed the way both systems cope with changes. Flexible system are based on fixed modules layout and hardwired control logic. If new requirements arise (i.e., process changes, fluctuations of demand) the system needs to be re-engineered in order to match such requirements. As aforementioned re-engineering might be a long and costly activity. Once again it is important to underline that FMS are really effective within the variation predefined during the design.
A flexible system can easily shift from a product to another within the same product family or in case there are little divergence. Then the effort to perform a product shift is not always difficult for FMS. Within the evolvable paradigm the requirements are directly mapped into modules. It is important to remark that the system is designed around process rather than product

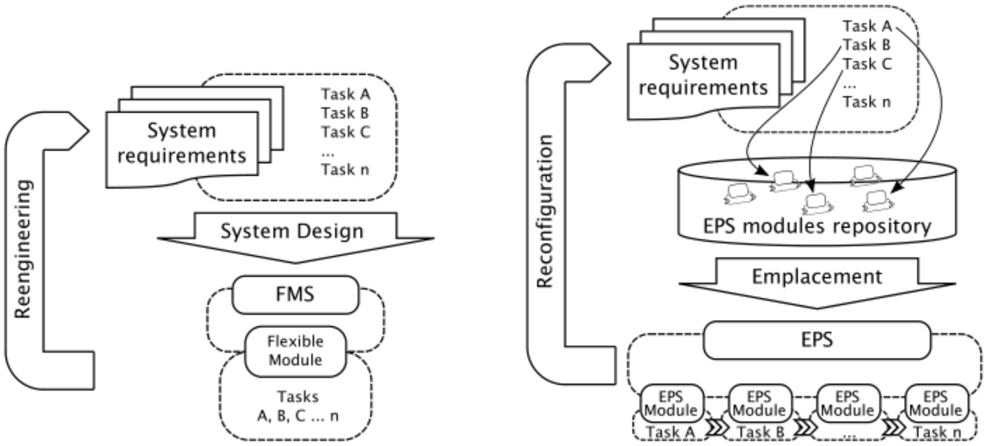

Figure 2.7: EPS vs FMS [27]

features, so modules are directly connected with the task to perform. Tasks and relative modules are matched within the *Emplacement*: it is a process in which the selected modules are physically put in place and logically integrated. The emplacement is needed every time new requirements rise. The line is then reconfigured. This opens the chance to adopt concurrent engineering.

It is clear how such a traditional flexible production system is not very reactive to adapt when new requirements are needed.

Underline the differences in life cycle in each system.
FMS system requires 4 phases:

1. Design of assembly line [*Product based design*]
2. Engineering
3. Testing of the new assembly system
4. Run

On the other hand EPS present 3 phases:

1. Design of assembly line [*Process based design*]
2. Configuration

3. Run

When one wants to change product, it will need to re-engineer the assembly line. This means that even for assembly the successive product of one already in production, I need to wait many month (need to do phase 2-3 again). This time has a cost in terms of lost production. Evolvable systems usually do not require to be re-engineered every time I need to change product, but they just need to be re-configured on-the-fly.

Nevertheless reconfiguration and re-engineering are two different processes. Taking advantage of the architecture framework, a full reconfiguration is available in hours, depending on the number of workstations involved. Re-engineering can last in some weeks due to the more complexity of the process itself. Mechanical and logical compatibility of the devices, connection of the process to relative.

An FMS has well defined work boundaries, based on thorough study of the product. On the contrary EPS has loose boundaries about the functionalities but it has very specific constraint for the interaction and the definition of the modules. EPS modules are defined after the codification of the assembly features.

2.4 Conclusive remarks

As seen above the possibility of reprogramming the resources and the computer-powered integration of tools for the design and management of the company has given an effective and quick manner to manage products variants.
On one side there is flexible automation with the capacity of to effectively and quickly produce a wide range of parts or products within a family. Evolvable automation, on the other hand, can manage a huge amount of processes thanks the skill concept. Since skill describe capability of a module, the production is seen as composition of modules, each one with proper

skills able to perform the required tasks.

The following table 2.1 summarizes most important features of the two paradigms:

	Flexible Automation	**Evolvable automation**
Equipment Logistic Assembly Product Design	Programmable transfer line and vehicles Robots CAM/CAD	Autonomous transfer line and vehicle Plug and Produce Machines Concurrent Engineering
System Architecture	Integral: Multiple task with or without tool changes Built in redundancy	Modular: Open and scalable Autonomous modules with embedded intelligence
Control Logic	Centralized Motion modulated by sensing and decision Robust with variable parameters	Distributed self-configuration self-organization adaptive
Driver of development	Product family	Process and hardware through the concept of skill
Target	Variants: Economies of Scope	Processes: Economies of skill

Table 2.1: Characteristics of FMS and EPS[27]

2.5 Economic models for traditional assembly systems

As stated from Whitney [2], costing for traditional system has been already formalized. A way to account fixed costs and variable costs is needed. Total Costs (TC) of making and assembling a product is the sum of Fixed Costs (FC), Variable Cost (VC), Material Costs (MC) and Other Costs (OC):

$$TC = FC + VC + MC + OC \tag{2.1}$$

The aforementioned relation is applied over the entire life cycle of production, but it is important not to forget that the different costs raise in different moments. Furthermore fixed costs are expenses which are incurred once the assembly plant is installed, before the production starts. Therefore to compare them one needs to allocate fixed cost to individual product units. The variable cost per unit can be determined quite easily, collecting data from a real system.
Material cost are ignored in most of the analyses because they will be the same despite the assembly system used, so they do not affect the decision.

Annual equipment cost In contrast to expenditures for material, energy and labour, in traditional manufacturing systems equipment for capital occur at a slower frequency than the rate of production. To compare these different cost patterns, one must make them homogenous equivalent quantities and it is useful to annualize capital costs in order to distribute them over the production volumes. In the determination of fixed cost is useful to mention the annual recovery method. The investment cost is converted in a sequence of cash flows occurring every year. The fraction paid each year using the mortgage amortization relation is

$$A = I_0 \left[\frac{r\,(1+r)^H}{(1+r)^H - 1} \right] \left[1 - \frac{\nu_H}{\rho\,(1+r)^H} \right] \tag{2.2}$$

A is the annual payment, I_0 is the investment at the time t=0, r is the interest rate. H is the minimum between the lifetime of the product and lifetime of the equipment component for non-reusable component. On the contrary for a reusable components H represent the maximum between lifetime of the product and the component. In last factor of multiplication ν_H represents the salvage value in case the equipment is taken out of service before period H.

It is defined the annual capital recovery factor f_{AC} as:

$$f_{AC} = \frac{A}{I_0} \tag{2.3}$$

It is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time. At the end the unit cost is given by:

$$C_u = \frac{f_{AC}(FC)}{V} \tag{2.4}$$

It is useful to remark that the cost of capital used to analyze public investments and private investments is different. The real cost of capital is a typical value used in evaluating public investments. For a private firm deciding to purchase equipment, the appropriate value is the interest rate charged on the loan modified by the inflation over the course of the payments. Whitney claims that flexible assembly system costs are a combination of variable and fixed cost. Basically FMS is a mixture of typical costs of manual assembly systems and fixed automation systems. It is going to be defined in the next paragraphs.

2.5.1 Unit Cost Model for Manual Assembly

Assuming negligible cost for tools and facilities negligible within manual production, the following relation expresses the production cost of a unit with a manual assembly system, which is obtained dividing the total cost of production by the unit processed in a period of time t.

$$C_u^{(M)} = \frac{C_l \cdot h_y \cdot p}{V} \tag{2.5}$$

in which V is the production volume and p is the number of operators involved in assembly process, expressed by the following relation:

$$p = \left\lceil \frac{\tau \cdot N \cdot V}{h_y \cdot s_h} \right\rceil \tag{2.6}$$

where:

N =number of parts per unit

h_y =number of hours per year

s_h = number of seconds per hour

τ =assembly time per part

C_l= annual cost of labour

The number of operators is calculated dividing the total productive time required for a given demand by the actual available production time. It assumed that each person can perform more than one task. Theoretically if the volume is very low such that the result of the eq. 2.6 is 1, all the assembly can be done by one operator.

2.5.2 Unit Cost Model for Fixed Automation

The main economic feature of flexible equipment is its ability to do more than one task. One may interpret this as the ability to be turned to a different application after a period of years, but more frequent and more important is the ability to turn to a different task after a few seconds or minutes. A typical assembly robot can assemble two different parts in a row, whereas a fixed automation assembly machine requires two workstations to do the same thing. The cost difference can be large: the cost of a second station compared to the cost of another gripper. Like dedicated automation and unlike a person, a robot can also work 16 or 24 hours per day. The economic consequences are that the cost of a robot assembly system does not have to grow strictly in proportion either to the required production volume, as manual assembly cost does, or in proportion to the number of parts in the product, as fixed automation does. Instead, one buys as many robots as their cycle time permits and the production rate requires, and at most as many tools as there are assembly operations, and runs the system as many hours as needed. For this reason, flexible systems' costs are a combination of variable (the number of robots needed) and fixed (the number of tools and part feeders needed). However costs is always an issue in manufacturing and in the choice of equipment, and cost is included in the flexibility concept, as the system's flexibility is dependent on how easily the system can transit from one stage to another. The number of workstation does not change. If the demand is higher than the expected one, it is usually not possible to expand the resources. Therefore, in that case, one must build another fixed line in parallel. This is a condition to avoid, since the purchase of another line is really expensive. So it is critical to have an exact forecast of production volume and trying to working at high saturation of the line.

For determination of flexible automation cost the assumption are the opposite: equipment cost is the significant one and labour cost is neglected. It can be expressed as follows:

$$C_u^{(Fx)} = \frac{f_{AC} \cdot N \cdot C_{ws} \cdot n_{ws}}{V} \tag{2.7}$$

where n_{ws} and C_{ws} are respectively the number and the cost of workstation installed in the line.

The number of workstation can be easily determined with the following relation:

$$n_{ws} = \left\lceil \frac{\tau V}{h_y \cdot s_y} \right\rceil \tag{2.8}$$

2.5.3 Unit Cost Model for Flexible Automation

Whitney assumes that each flexible workstation needs a different tool to hold each piece in the assembly. Moreover a flexible automation system needs also the presence of human operator directly involved in the process whom cost must be accounted in the unit cost determination. The following relation is a combination of equipment cost and labour cost:

$$C_u^{(Fl)} = \frac{f_{AC} \cdot I}{V} + \frac{L_s \cdot I}{V} \tag{2.9}$$

where f_{AC} is the aforementioned annual capital recovery factor, I is the total investment in resources and tools.
The latter can be expressed as:

$$I = (n_{ws} \cdot C_{ws} + n_T \cdot C_T) \tag{2.10}$$

where the quantity which were not defined yet are:

L_s=annual labour cost

n_T =number of tools

C_T = cost of tools

and the number of workstation needed can be calculated as:

$$n_{ws} = \left\lceil \frac{\tau n_p V}{h_y \cdot s_y} \right\rceil \tag{2.11}$$

After having presented how to calculate units costs in all the cases, there is a qualitative comparison of units cost for the three kinds of assembly resources in relation to the expected production volume in a period. Manual assembly is effective with low volumes due to the lower cost of a wage and because each operation can do more than one task. For high volumes fixed automation becomes the most effective because the working conditions approach the saturation. Flexible automation in the presented comparison is never the low

cost. The combination of high equipment cost and low productive volume makes the cost per part relatively high for FMS. Thus production capacity of a flexible system is usually lower than dedicated line.
Nevertheless in order to find which is the best system for a given case, one must consider also other parameters, like as the opportunity of the FMS system to be converted to other productions.
Finally, in that dissertation configuration costs are never taken into account. Those are supposed to be critical in the comparison between evolvable paradigm and flexible automation. So there is need to find other ways to express cost for manufacturing.

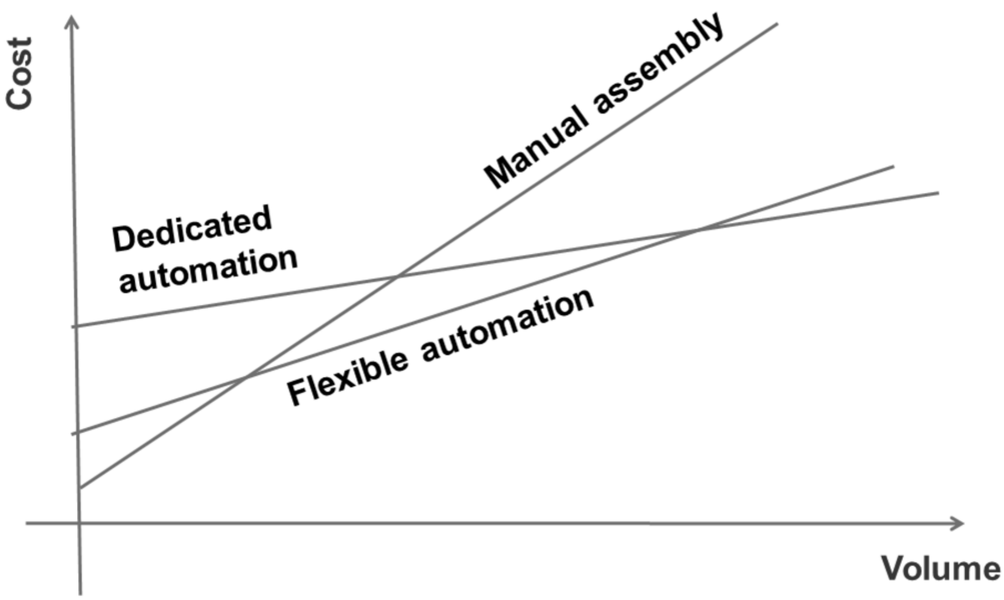

Figure 2.8: Assembly systems

2.6 Life cycle cost

Molinari Tosatti [6] proposes a life cycle cost calculation for investment decisions.
Life Cycle Cost (LCC) is a design process for controlling the initial and the future cost of ownership of a good.

This analysis is generally used in evaluation of the total cost of an object from the purchase to dismantle, taking into account all the costs incurring during lifetime ([19]). Thus for a given production solution LCC is the the total cost to produce over a given time horizon accordingly with a given production.
According to such a model the LCC is represented as the expected NPC (Net Present Cost): all the cost occurring along the lifetime are summed and discounted. Methodology of calculation is divided in three steps:

- Definition of the demand scenarios. It is based on the identification of expected events occurring over the time horizon previously defined.
- Definition of the available configurations. One should perform a reconfigurability analysis in order to consider the potential effects of demand fluctuations on the analyzed solution.
- Calculation of the cost for each configuration in each period. Three classes of cost are considered:
  - Investment cost: I_t is the portion of investment paid at period t
  - Fixed Cost FC_t
  - Variable costs VC_t^j, s. Variable cost for configuration j in scenario s at period t. Those are the costs depending on the demand and they are different for each configuration. This term, includes operation cost (e.g., energy,warehouse inventory, handling costs), maintenance costs, cost for lost production (if there is capacity shortage or technological limitations) and reconfiguration costs.

One should note that not all of the cost categories are significant to all projects. The preparer is responsible for the inclusion of the pertinent cost categories that will produce a realistic LCC comparison of project alternatives. If costs in a particular cost category are equal in all project alternatives, they can be documented as such and removed from consideration in the

LCC comparison.
Given one time horizon starting at period t_0 with T periods of production. Given s scenarios, each of them occurring at period t occurs with likelihood $p_{t,s}$the lifecycle cost through T periods is calculates as:

$$LCC_t = \sum_{t}^{T} \frac{I_t + FC_T + \sum_{s=1}^{s_t} \left(p_{t,s} \cdot minVC_{t,s}^{j} \right)}{(1+\rho)^t} \tag{2.12}$$

where ρ is the rate of interest, the other variables have already been defined previously.

One can define demand scenarios in different ways: fixed demand scenarios, deterministically variable scenarios or stochastically variable scenarios. An interesting decision making tool has been found in the literature review. It is proposed to evaluate assembly costs of micro-products and to compare different assembly strategies for a given product or product family[31].

Silver and de Weck, [22] show how to handle costs for complex systems with Time Expanded Decision Network (TDN). In this case is described the methodology to design and analyze flexibility in large-scale complex systems as Heavy Lift Launch vehicle for NASA's space exploration initiative. Increasing flexibility of a system allows a lowering of future *switching costs*. Switching cost can be expressed in term of money or as the time it takes to change configuration.

Life cycle cost of a system configuration, as function of demand d and number of periods t, can be estimated as:

$$C_{lc}(d,t) = C_{Di} + C_F \cdot T + \sum_{j=1}^{T} C_{V_j} \tag{2.13}$$

Assuming that C_{Di} is the cost for initial investment which means it arises at the beginning. Every investment for a new configuration it is included the switching cost term C_{sw}.
C_F are fixed cost, those incurring in every period independently from demand (e.g., labour, facilities, overhead).

C_V is the term of variable costs, the one which vary depend on demand trend. It includes operating costs, production materials and variable labour cost.

2.7 Comparisons in literature

Here there is a review of some comparison found in literature. Same of the methods are based on quantitative economical methods, whereas some others use other qualitative approaches.

2.7.1 Economical Comparison

Fujii [35] proposes an economic analysis between two high productive volume automated system: a high-volume flexible manufacturing system (HV-FMS) for agile manufacturing and flexible transfer lines (FTL). The model estimates the economical behavior of the two systems under several demand patterns which have been generated from historical data. Both models are simulated to evaluate the effectiveness of HV-FMS from an economical view point. The system's effectiveness is measured by net profit P. Having a time period of T years, the net profit P is obtained from total sales substituting an operation cost, a cost for equipment change, a cost for equipment expansion and an initial investment, as:

$$P = \sum_{t=1}^{T} \frac{(1+u)^t \, pV_t}{(1+\rho)^t} - \left(\sum_{t=1}^{T} \frac{C_t + F_t + A_t}{(1+\rho)^t} + C_0 \right) \tag{2.14}$$

where ρ is an interest rate, p is a sales price vector of products and u is its inflation rate, V_t is a production amount vector, C_t an operation cost, F_t is a cost for equipment expansion, A_t is a cost for equipment change of $t-th$ year, and C_0 is an initial investment. Note that F_t is induced for responding the change of product mix and additional equipment to make up for a lack of productive capacity.

The initial investment for equipment HV-FMS is estimated by summing all the element composing it, as follows:

$$Co = c_M + n_M + c_T n_T + c_v n_v + c_c n_c + c_p n_p + Z$$

where costs and total assigned numbers of machining cell, processing tool, AGV, palette changer and palette are c_M, c_T, c_v, c_c, c_p and n_M, n_T, n_v, n_v, n_p, respectively, and Z is miscellaneous cost for system construction.

The operating costs C_j for $j - th$ year is estimated by the sum of costs of materials, personnel, inventory, repair, energy, processing tool, supplement materials and preservation U. For the other production system a similar cost relation as been used.
Once the cost expressions have been defined, the comparison is carried out by a numerical analysis and the results are shown as charts of cash flows occurred along time horizon established. For the complete procedure, see at [35].

2.7.2 Other approaches

In literature other approaches for comparison of manufacturing production systems have been found, not strictly based on economical evaluation.

Multi-objective decision model A multi-objective decision model is presented by Demmel and Askin [32]. They pointed out that investments in advanced system technologies are difficult to justify using ordinary financial measures. Common discounted cash flow measures oversimplify the investment decision. Traditional methods are unable to deal with intangible benefits such as greater flexibility, shorter lead time and increased knowledge in the use of new technologies. Furthermore traditional methods assume a static environment for the do-nothing alternative. Therefore evaluation requires improvements to include all those intangible factors.
The model encompass three objectives:

- Pecuniary
- Strategic
- Tactical

Pecuniary objective addresses costs using traditional Net Present Value (NPV) methods to outline a cash flow analysis for each alternative under. NPV is expressed as usual:

$$NPV_j \sum_{t=0}^{T} \frac{Y_{tj}}{(1+r_t)^t}$$

with Y_{tj} the after tax cash flow of alternative j and r_t rate of interest at time t. The great Strategic and tactical objectives include qualitative considerations. Nevertheless they are defined using a non monetary index based on verbal ratings Q_{tkj}, with $0 \leq Q_{tkj} \leq 100$. The qualitative flow $NPQF_j$ is defined as follow:

$$NPQF_j = \sum_{t=0}^{T} \frac{Q_{ktj}}{(1+h_t)^t}$$

where $NPQF$ is the expected performance and h_t is q a qualitative discount rate indicating a decision makes' impatience for benefits. In this way the quantities are homogeneous and they can summed and a numerical study can be carried out.

After being defined the indexes, the comparison between flexible and not flexible automation is performed using two-stage convex quadratic mixed integer programming and control theory.

Analytical comparison Zhang[29] presents an analytical and qualitative comparison among different manufacturing systems. These manufacturing systems (DMS, AMS, FMS, RMS) are compared from view point of life cycle cost, adaptability, complexity, production rate, reconfiguration time and ramp-up time. Authors stated that a quantitative comparison would need gathering a lot of data. Moreover for one of the system, RMS, data were not available at that time. Then the comparison is made possible by using qualitative indexes called Satisfaction Degree Index (SDI).A SDI is meant to be the degree of satisfaction of a system performance. It can be varied between 0 and 1 which mean respectively, the worst performance and the best one. He provides a list of the cost occurring during the life cycle of a generic production system:

- Design Cost: includes all the costs needed in the design of the system phase: process planning, engineering design, testing, evaluation.
- Manufacturing/Implementation Cost: most important cost term. Includes material cost, labour cost, equipment cost and management cost.
- Reconfiguration Cost: layout design cost and reconfiguration operation cost
- Ramp-Up Cost; cost for recovering the system performance
- Operation Cost: cost to run the system
- Remanufacturing Cost: cost for recycling the system or disposal it after the end of the life cycle.

In this article cost are assumed being proportional to time. For each of the category of cost is assigned a SDI. It is designated a weighted coefficient for each cost term and then all the indexed are summed. The manufacturing paradigm with the higher SDI results the more suitable for the scenarios depicted.

2.7.3 Quantifications of Flexibility

Many different attempts have been carried out in the past years for quantifying flexibility. As many authors have observed, the quantification

of flexibility, even though approaches for its evaluation in the investment decision-making are few, is difficult to be handled and mostly limited to special cases (Abele, [14]).
One interesting tool has been proposed by Georgoulias [15]. The DESYMA (Design of Systems for Manufacture) is another approach based on measuring flexibility with the help of demand probabilities. It further combines economic measures, sensitivity analysis and manufacturing performance measures in an integrated manner. The Discounted Cash Flow (DCF) of the system is calculated for each market scenario and the spread of the DCF scores defines the flexibility of the system in the given market environment. The problem of calculating the minimum DCF_i for the market scenario demand $D_i(t)$ over T periods of time can be formulated as follows:

$$DCF_i = I_0 + min\{\sum_{t=1}^{T} \frac{O_m(t) + S_{km}(t)}{(1+\rho)^t}\} \tag{2.15}$$

subject to the condition

$$C_m \geq D_i(t)$$

where:

I_0 is the initial investment

$O_m(t)$ is the total cost for for period t

$S_{km}(t)$ the switching cost for period t if configuration k is assigned for period $t-1$ and configuration m is assigned for period t

C_m is the capacity of the m-th configuration

ρ is the rate of interest, supposed constant for the whole T

This method is suitable to measure flexibility in case of lines and work places according to volume fluctuations. DESYMA can be applied under theoretically all circumstances, but it is more appropriate for mid or long-term evaluations. This approach seems to be suitable even though it is not mentioned the possibility to split the investment over the different productions or to allocate resource if they are needed and when they ware needed.

Hutchinson and Sinha [4] mean flexibility as the ability to change manufacturing mission and capacity. Using a theoretical approach for a comparison model based on choice between either a flexible manufacturing system or transfer line, and with the assumption that the system will meet the life cycle production for a new product for which the demand is known only statistically. In the numerical example considering standard deviation of demand as the measure of uncertainty, it is shown the value of flexibility in economic terms. They propose a comparison between flexible manufacturing system and dedicated transfer line system. It is highlighted the handicap which affected previous comparison analyze evaluations: the potential benefits of flexibility were not included in the evaluations. In particular it is introduced uncertainty. The demand is seen as a normally distributed random variable and standard deviation of demand is used as a measure of uncertainty. Short-term fluctuations in demand are modeled as noise in the system.
The model proposed estimate NPV and uncertainty. The decision maker seek a balance between the two tradeoffs: FMS allows to split the investment for capacity in two steps, a part at the beginning initial investment purchasing a limited productive capacity and further investments in case the demand increase exceed the productive capacity. Capacity can be expanded with minimum fixed costs. On the other hand transfer lines require higher investment at the beginning because it is the only opportunity to acquire capacity. The comparison is carried out with the requirement to meet the life cycle production and maximizing expected NPV.

2.7.4 Evaluation of changeability

Hartung [7] proposes an expression for changeability costs C_c:

$$C_c = C_o + x(C_{pd} + C_{pi}) \tag{2.16}$$

where

- C_o = Object costs
- x= Frequency of change, meant as the number of changes in the lifetime considered
- C_{pd} = Direct operational costs
- Indirect operational costs

The equation 2.16 portrays the development of changeability costs during the lifecycle. The initial level of the changeability costs depend on the object cost, namely the initial investment, and increases by every change along lifecycle. In particular the mathematical relation put in evidence how changeability costs are determined: in case of low frequency object costs are predominant; in case of high frequency of change process cost are prevalent.

There are two main categories: Object costs and Operational Cost.
Object cost are:

- Initial, first and construction investment costs
- additional investment cost

Then there are Process costs, which are further divided in:

- Direct operational costs
  - adjustment, modification
  - recovering process capability
- Indirect operational costs

- unplanned downtime
- work overtime
- warehousing

Chapter 3

Problem Definition

In this chapter it is introduced the problem to study, which comes from the detected lack in the literature and it is defined the aim to reach with this work. Two are the main contributions: the first is the cost model for EPS and FMS, the second is a comparative cost analysis between the two systems.
From the literature review, essential preliminary research work, appeared the need of economical considerations about evolvable system, especially in regard to traditional automatic assembly systems.
FMS and EPS might appear similar since both have to do with the flexibility. So a clear definition of what *'flexibility'* means was considered fundamental for the comprehension of the differences in the systems' dynamics.
FMS has *internal* flexibility, namely the assembly system requirements delineated during design phase are set up in order to deal with volume changes and to assemble a bunch of different products belonging to a product family. Therefore the line is built up with predetermined boundaries. Of course, the line is flexible being able to be re-used for several product generations. Nevertheless each time that new requirements occur the line needs to be reconfigured. In other words, an FMS is very flexible for what it was designed to do, but it is a quite rigid and rarely agile system so it usually takes a lot of time and effort changing once they are already running.

On the contrary evolvable paradigm implies agility and easy reconfigurability. It can change in many different ways in order meet new requirements. First of all an EPS can re-organize the current resources to adapt to new task. If the current resource are not suitable to accomplish the new task, one can add *task-specific* and *process-oriented* modules. Thanks to the Multi- Agent System, modules do not need to be integrated in the legacy system. So then evolvability enables both *external* and *internal* flexibility.

3.1 Cost Model

The purpose of the proposed model is to determine cost-effectiveness of alternative investments and business decisions, from the perspective of an economic decision maker such as a manufacturing firm (the Company).
The analysis aims to define the circumstances which make advantageous the adoption of an EPS system. In particular the comparison focuses on the costs of purchase and utilization of an automatic assembly systems throughout multiple production cycles. What is crucial for the aims of this work is to identify the most important terms to be accounted to represented the cost behavior of the system. Furthermore one critical aspect is how to consider configuration cost during a transition to a new production cycle.
In the previous chapter it has been shown how an economical analysis can be treated: that approach will be developed and adapted to this particular context.
An automatic assembly system is depicted accordingly to the product to be processed. In particular one should focus on the processes to be done for getting the assembly accomplished.
It is assumed, for sake of simplicity, that the expected assembly process consists of:

- description of the product in terms of the sequence of assembly operations required (*work-flow*)

- description of the innovated manufacturing system in terms of set of EPS modules and their aggregation into workstations.

In the model each task is performed by one workstation. According to this assumption (which defines the *expected final level of accuracy*), a mathematical formulation of a simplified economic model has been built up.

More interesting flexibilities for an automated assembly system are:

- Product flexibility: describes the ability of the production system, to produce a changed set of products without serious updates and replacements of the present resources.

- Mix flexibility: describes the ability of a system to produce a number of different products at the same time.

- Volume flexibility: describes the ability of an assembly system to vary the volume of products without remarkable consequences on production costs.

In this analysis there will be taken in account Volume flexibility and Product Flexibility. The purpose is to determine the trend of costs for both a EPS and a FMS during the system lifespan. In order to sum costs that raise in different time periods, an opportune interest amount it is introduced. Thence future costs need to be depreciated. This makes the cost homogeneous financial quantities, that can be summed.

3.2 Comparative Analysis

Once the model has been formulated, it was used for developing the comparative analysis, which disclose what are the general circumstances which make EPS more convenient than FMS. In the comparison just the cost terms that are not in common for the two systems have been taken into

account.
As it will be pointed out in the next chapter, expressions in the cost model have similar structure for both systems. The comparison will be accomplished considering costs for equipment purchase and all the needed costs for making the production possible. Thus the object of the cost analysis is the assembly system purchase costs and the reconfiguration costs.

The analysis was carried out varying some parameters, such as number of product generations during which the system is working, number of task involved in the assembly work-flow, rate of evolution of the system and finally the ratio between the hypothesized equipment cost of a flexible and an evolvable system one.

3.3 Limitations

A complex system like EPS would deserve a thorough economic analysis. This is not possible at this step of the research since the evolvable paradigm has not full matured embodiment yet. Thus an accurate cost accounting methodology is far beyond the aim of this work.
The economical evaluation is a very complex problem and it can be handled in many different ways. In the work presented by the author a simple and intuitive approach has been preferred. Of course the presented approach is not the most accurate representation of the way evolvable system should actually work, but it is a first approximation. Indeed, according to the evolvability paradigm, every basic operation is logically expressed by a skill. A coalition of atomic skills forms a complex skill. Each skill has its embodiment in a *task-oriented* module. In the model proposed in the next chapter, every workstation will be dedicated to a process task, meant as complex task.
As already depicted in the previous chapter, it is appropriate to point out that EPS and FMS systems are not always applicable to the same type of activity. In other words the main vocation of evolvable systems is not

just to replace the flexible systems, but the opening of new and alternative productive scenarios. The approach differs for the object around which the system is built. While the flexible system is designed with the aim to produce a product or a family of products, the evolvable looks at the processes that compose a sequence of assembly.
In EPS context workstations are composed by modules chosen and assembled to respond to productive tasks at the time that they occur.
Finally some common suitable working conditions for both paradigms have been detected: medium or low production volumes and variable demand. This will be the domain of this work.

Chapter 4

Cost Model

4.1 Literature Concepts

4.1.1 Variable and Fixed Costs

Costs are divided up into categories. The very first distinction is made separating fixed costs from variable costs. The discriminating factor is how each cost item varies in relation to the variation of volume of output. This is usually useful in determination of unit cost of a product. After that the main distinction on which the model is based is the discrimination between direct and indirect costs. A brief introduction of those categories is here reported.

Variable Costs Variable Costs are costs whose overall value varies according to the output level. It can vary proportionally to the output level. For instance, if the output volume grows of 10% then variable cost will increase of 10%.
If a cost is defined as variable it must be clear which is the output activity. In other words, to be variable a cost needs to be variable depending on something else. It is important to remark that the cost variable distinction is made assuming a reference period, Usually the output activity which determines the variability of costs is the productive volume, namely the

number of unit processed.
Typical variable cost are electricity, inventory management, logistics, maintenance, and so forth.

Variable cost can be easily distributed on the production to define the production cost of a product.

Fixed Costs A fixed cost does not change with the variation of output activity level. Fixed costs can change with time but independently from productive volumes. Typical fixed cost are building purchase, facilities and overheads. Another cost which is independent from the throughput of production are licenses for the control system software.
As aforementioned in the literature review, the traditional approach consider investments for setting up the line as a fixed cost. This is true if such investments is usually made once in a lifetime, during the design phase. Thus they are made before the begin of each new production, so they are independent from the demand, at least as long as the demand is not higher than the productive capacity. Nevertheless adjustment costs are incurring many times during the life of an assembly system but they grow with the number of production shifts.

Labour Cost Labour cost is a bit tricky, because it is may be accounted as fixed cost or a fixed cost depending on the way the worker are employed in the assembly line, whether the human workers' wage is proportional to the production level or not.
It is usual to treat labour as variable cost in economic analyzes. Strictly speaking this is not true. Generally union contracts protect factory employees from being fired. Nevertheless it can be considered as a variable cost. Indeed if the assembly process become more complex, with more workstations, more workers are needed.In case of reduction of production volumes, human resources can be employed for other activities.

4.2 Building the cost model

There are 3 steps in the model:

1. Identify relevant cost elements for comparison;

2. Express the configuration cost according to the production volumes and the number of production shifts. The link between the volumes and the cost is the number of workstation needed;

3. Analyze the trend of identified costs over the assembly system lifetime.

In turbulent market conditions, systems need continue adjustment, namely new investment to adapt the assembly line to the market requirements.
In order to distinguish investment from other fixed cost not directly connected with the dynamics of the system, investments will be treated as stand-alone category. Nevertheless it is not really useful to treat those costs, classifying them into fixed and variable categories, because theoretically each module can be shifted from a productive cycle to another. Thus this model will focus on direct cost for purchasing, setting, running and reconfiguring an automatic assembly system throughout multiple production cycles. Thus for the characterization of cost associated to the purchase, installation and production of an automatic assembly system direct costs are considered. Direct costs are those which are directly connected to the assembly system and with its lifecycle.

Then cost encompass in the model are:

- Equipment investment

- Reconfiguration and adjustment cost

- Operating costs

Indirect costs will not taking in account for this model since they are not tightly connected with the assembly system, but with the firm activities. Activities do not For instance, overhead are expenses that a firm must face but they are not directly linked with the processes but rather with the firm management.

Equipment Investments

Investment is represented by the cost of the workstation and its building blocks. In EPS domain, it is represented by the cost of the modules and the platform which compose the system. Equipment components are general purpose equipage and they have high residual value. One must allocate these costs on the current installation just for the fraction of the useful lifetime of the modules that is exploited by such installation. In order to allocate the fraction of cost, the expenses for equipment is distributed among the years through the annual payment. Annualized capital capital costs can then be easily charged on production volume. That is one of the cost elements for the determination of unit production cost. Investment cost compass robots/module, platforms, tools, fixtures, feeders, conveyors.

Configuration Costs

This category refers on how much costs putting the workstations together for a given production. Given one system configuration, demand variations and new assembly processes to implement provoke reconfiguration, then cost to be incurred by the firm. Then reconfiguration cost represent additional expense raised every time system needs adjustments. It is alto refers to the cost of switching from a generic configuration A to another configuration B. Since reconfiguration costs depends on agility of the system it is not easy to quantify in a general way.

It is important to stress that, as the other quantities involved in this dissertation, this cost is tightly connected with the focal process so it is impossible to quantify it in a general framework, but it should be measured in a real case. Thus a simple analytic expression has been used herewith and it is presented in the next paragraphs.

Operating Costs Operating costs occur for daily operation of the assembly system. They encompass a lot of cost factors as labour cost, material cost, energy cost, quality control cost, material handling and inventory handling, waiting time and idle time cost, quality costs, logistics cost, maintenance cost.

The first step of a cost accounting model is the definition of the cost object.
Objects of this study are costs of acquisition, operation and conversion of an assembly plant during its life cycle. In a turbulent market environment fluctuations may require systems reconfigurations to face production volume or different assembly work flow.
As already pointed out previously, the cost of an assembly system is based on the distinction between fixed costs (FC) and variable costs (VC).

Basically the expression for total cost is

$$TC = FC + VC$$

In order to describe the cost for an EPS system one may consider that theoretically all the resources can be transferred from a productive cycle to the next. Thus instead than considering the distinction between direct fixed and indirect cost, it is more useful express cost in terms of direct and indirect cost.

As seen in the literature review, if one considers the entire lifecycle cost of a manufacturing system in an uncertain environment, evolvable systems can be less expensive than flexible ones. The main economical advantage of EPS compared to traditional automatic systems is that EPS capabilities are installed if more production capacity and functionalities are needed and precisely when they are needed. A general way to express life cycle cost calculation for an assembly system is depicted by eq. 4.1

$$C_t = \sum_t \frac{I_t + Cp_t + Co_t}{(1+r)^t} \tag{4.1}$$

where:

- I_t: the portion of the investment, referred to the focal system configuration
- Co_t: Operating costs at period t
- Cp_t: Configuration costs period t
- r : rate of interest

4.3 Cost EPS

The purpose of such a system is to distribute the investment on a longer period than the lifespan of a product. New modules will be provided only if they are needed and when they are needed. It is possible to express the total cost of purchase, installation and use of the line as shown in eq.4.2. The first three terms are the most significant ones. The first relates to the costs of purchase of the platforms on which workstations are connected, the second is the cost of purchasing the workstation. Finally, the term C_P represents the cost of line configuration.

$$C_t^{(E)} = \sum_{t=0}^{t_n} \frac{\left[\left(\sum_{j=1}^{n_{pl}} f_{plj} C_{plj}\right) + \left(\sum_{i=1}^{n_{ws}} f_{ws_i} C_{wsi}^{E}\right) + C_o + C_p^{(E)}\right]_t}{(1+r)^t} \tag{4.2}$$

where:

- n_{pl}, n_{ws} = respectively number of platform and number of EPS workstations
- f_{pl}, f_{ws} = annual capital recovery factor, respectively about number of platform and number of EPS workstations, it is possible to obtain it from the standard mortgage amortization formula: $f = \left(\frac{r(1+r)^n}{(1+r)^n-1}\right)$
- $C_p^{(E)}$= configuration cost
- r= rate of interest
- Co_t= Operating costs at period t

4.4 Cost FMS

For the flexible system the structure of the equation is the same. As portrayed in (eq.4.3) there is equipment cost for workstation and handling system ($C_{ws}^{(E)}$), configuration cost and operating cost.

$$C_t^{(F)} = \frac{\sum_t^{t_n} \left[\left(\sum_{i=1}^{n_{ws}} f_{ws_i} C_{wsi}^{E} \right) + C_h + C_o + C_p^{(F)} \right]_t}{(1+r)^t} \tag{4.3}$$

where C_h is the cost for handling (e.g., conveyor). Within evolvable domain handling can be accounted into the modular platform cost.
It is notably the inverse weight of the integration costs and purchase cost in the two different domain, as depicted in fig. 4.1. If one consider the sum of equipment cost and reconfiguration cost for both systems: FMS on one hand requires low investment in the purchase of workstations, but on the other hand needs higher integration and installation costs. For EPS will be the opposite. Indeed in an evolvable system workstations are more expensive[1] but it is easy to configure and to add modules.
Parameter α is properly defined as *cost factor* and it is the ratio of evolvable workstation cost to flexible workstation cost:

$$\alpha = \frac{C_{ws}^{(E)}}{C_{ws}^{(F)}}$$

In order to count this variability into the model, it will be calculated the trend of the cost curves with different values of α.
There are some assumptions that must be done to handle the problem.

1. The product are composed of n_k parts which requires a single task to be assembled
2. Each task is accomplished by an automatic workstation
3. The cost of new workstations will be incurred during the period in which it was bought

[1] It refers to the expected cost of an evolvable workstation. Up to now there is not any evolvable plant installed in an industrial environment

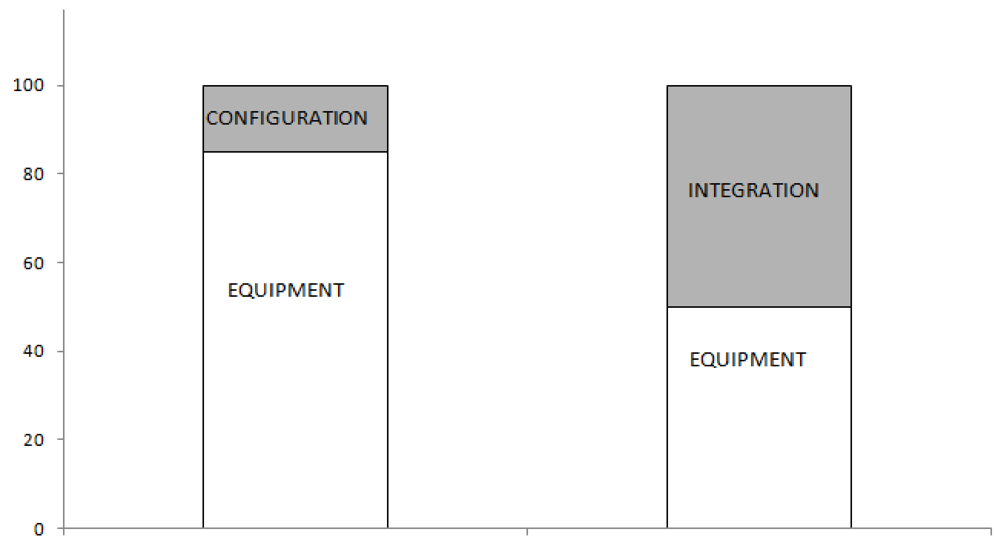

Figure 4.1: Cost breakdown in the two systems

4. The cost of reconfiguration arises whenever there is an adjustment in the shop floor

4.5 Configuration costs model

It is difficult to quantify configuration and reconfiguration costs in a general discussion.
So some simplifying assumptions about cost trend for both system need to be introduced. The reconfiguration costs raise when new requirements from the system come up. This is usually caused by an unstable market which changes, either in terms of volumes or in terms of product features.
As documented in literature within flexible paradigm, new product manufacturing can require a new integration of the system which is a quite long and costly operation. The reconfiguration phase for an evolvable system consists of a series of operations like rebuilt mechanical and logical interface, and it may vary from product to product.
The reconfiguration in an evolvable system would require to set the workstation up with new parameters if the processes of the workflow meet the skill

of the modules already available in the job shop. In case new modules are needed, the Company can ask for new modules to the module supplier.
One of the most disruptive features of an EPS module is its ability to self-configure once it is connected to the modular platform, becoming active part of the system immediately. From this description it is acceptable to think of cost for the reconfiguration as lower than traditional systems and it is linearly proportional to the number of workstations. The cost of the new module, seen as new investment, is accounted within the period of time they are actually in use. Therefore costs of the investment are distributed on the focal production and allocated on the product assembled.
Flexible system presents a more complex context during renewal of the assembly system. The reason is to attribute to the lack of well structured procedure for reconfiguration beyond the flexibility limits. The re-engineering of the line is usually connected to the system integrator experience and its know-how.
As aforementioned new system requirements can be met with a quite simple reconfiguration whether the changes of process are within pre-determined flexibility limits. Otherwise re-engineering is a long and complex phase.
In order to disclose distinctions between large and small changes re-engineering cost are expressed by means two different expressions.
As shown in fig. 4.2 costs of reconfiguration are linearly proportional to the number of stations for the evolvable. (eq.4.5).

$$C_p^{(E)} = c_1 n_{ws} \tag{4.4}$$

As already mentioned, configuration cost in a flexible line are assumed to grow linearly with the number of workstation. It noteworthy remark that cost for renewal of the line will be substantially higher for flexible systems if a complete reconfiguration is performed, as seen in eq.4.5

$$C_p^{(F)} = c_2 n_{ws}^b \tag{4.5}$$

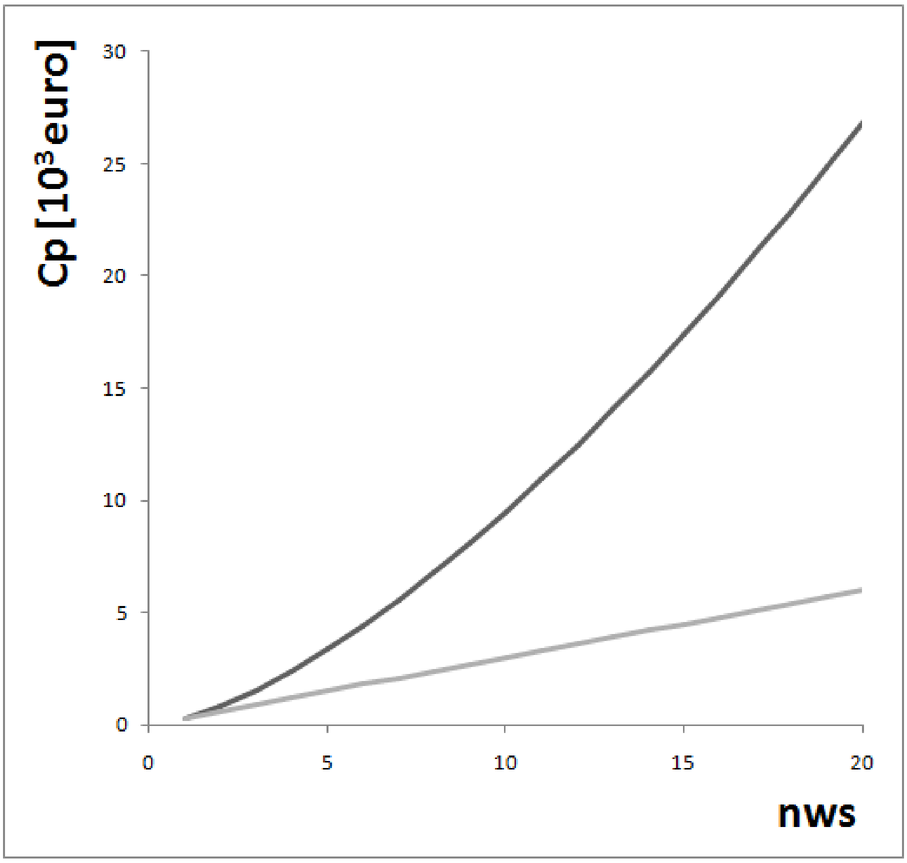

Figure 4.2: Configuration costs as function of number of workstations in both systems

being c_1, c_2 coefficients whom value is expressed in currency and b an appropriate value $1 \leq b \leq 2$.
Probably the cost raise more than linearly with workstation number since one should take in account that re-engineer in workstation does not involve just setting the workstations themselves but even to re-establish the connection between the workstations. In other words, partial electro-mechanical interfaces need to be rebuilt and a massive work of control logic must be carried out.
Assuming 4 workstations to be connected as depicted in fig. 4.3.
What will be the number of configuration and connections to make for integrate all the workstations together?
With the purpose to give an overview on the complexity of programming

and to briefly display the number of programs to be carried out in the case of flexible system, given n machines, using a matrix representation.

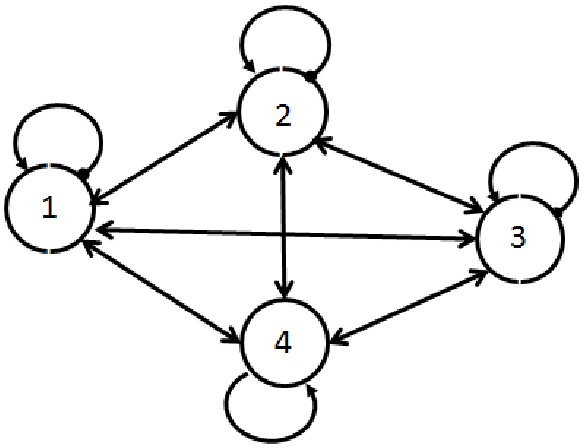

Figure 4.3: Graph representation of assembly line

The matrix with size $n \times n$ is symmetric ($C_{p_{ij}} = C_{p_{ji}}$). Columns and rows represent the i-th machine to connect to the other. The terms on the diagonal are the configurations of the machines through the central control system, those off-diagonal the number of connections between two different workstations. For example, it is assumed that once connected workstation2 with workstation4 there is no need to programm once again the same. $2 \leftrightarrow 4$.

$$\begin{bmatrix} x & x & x & x \\ & x & x & x \\ & & x & x \\ & & & x \end{bmatrix}$$

According to this way of thinking, integration and programming costs for flexible systems can be also expressed as follows:

$$C_p^{(F)} = \sum_{i=1}^{k} \left(C_{p_i} + \sum_{j=1}^{M} C_{p_{ij}} \right) \tag{4.6}$$

The maximum number of configurations to do in case of reconfiguration of all the workstations can be expressed as the number of element in the matrix:

$$n = n_{ii} + nij = n + \binom{n}{2}$$

with

$$\binom{n}{2} = \frac{n!}{2!(n-2)!}$$

For a modular system as EPS one just need to configure workstations. In the matrix representation correspond to have a diagonal matrix, with all the elements off-diagonal are zero. Note that this representation is not a calculation tool, but just a qualitative way to express the growing complexity of the programming depending on the number of units (e.g. workstation) in a integrated, centralized control architecture.

4.6 Model Validation

In developing of any model, the question of validation arises.
Validation consists in ensuring that a model fits well the actual phenomenon studied. The measure of which a model should be valid is based on its intended usage. For instance, a rough-cut mode is usually lower in validity than a detailed one: a deterministic analytical or parametrical model can be enough for the former, while a detailed simulation might be necessary for the latter.
Contextually to validation one must consider tractability. Tractability is the ease with which a given model can be used. Usually,high-validity models are low in tractability, and the contrary.
If the scope of the problem under investigation is too large, many other simplifying hypotheses are necessary in order to keep the model tractable:

- effectiveness of the system: no setups, no breakdown and no rework

- no warehousing
- the effort associated with the production shift varies depending whether a process change (e.g.evolve) or it does not change. Reconfiguration and re-engineering cost depend on the complexity of the system

The assumption that reconfiguration and integration costs increase respectively linearly and in power b with the number of the workstations depending on the complexity of the system is likely the most contentious.
Measure the complexity of a system is not possible in a general dissertation. Nevertheless one can suppose that in a certain way the number of workstations is linked with static complexity.
An integrated architecture as the one of traditional flexible systems, a large number of workstation implies an hard work of setting up the line. Therefore if there are more stations to be integrated more effort is needed, not just for configuring each block of the line but even for integrated them. A modular structure with distributed control, on the other hand, allows to concentrate reconfiguration efforts on each single module. If there is need to change tasks one can just change it without any effort in integration as well.
So if reconfiguration cost grows linearly with the number of workstations it is reasonable that cost for re-engineering will grow with power b.
Noteworthy it to remark that the only way to be determine with certainty how good these assumptions are, however, is to resort to exhaustive empirical research, which is beyond the scope of this thesis since evolvable paradigm is not a mature industrial reality yet. Thus, no further efforts were taken to validate these assumptions, and the fact that the results are based upon certain simplifying assumptions is consequently stressed.

Chapter 5

Comparative Analysis

The model takes into account cost which occur differently in order to put in evidence the differences between two systems. In this chapter it is presented the comparative analysis.
A numerical examples is proposed in order to examine the cost behaviors within many different scenarios, trying to determine which are the suitable conditions for one or the other system.

5.1 Calculation procedure

Admitting to have a flexible or an evolvable system, one wants to see what will be the qualitative trend of costs. The decision maker needs to choose between the FMS and EPS alternatives.
Starting with an assembly work-flow of N_s steps (fig5.1). Each step in the production flow is a process, a task to be accomplished.

5.1.1 Number of workstations

First of all, in order to design the system, demand trend is given. According to the demand one can define how many workstations are needed.

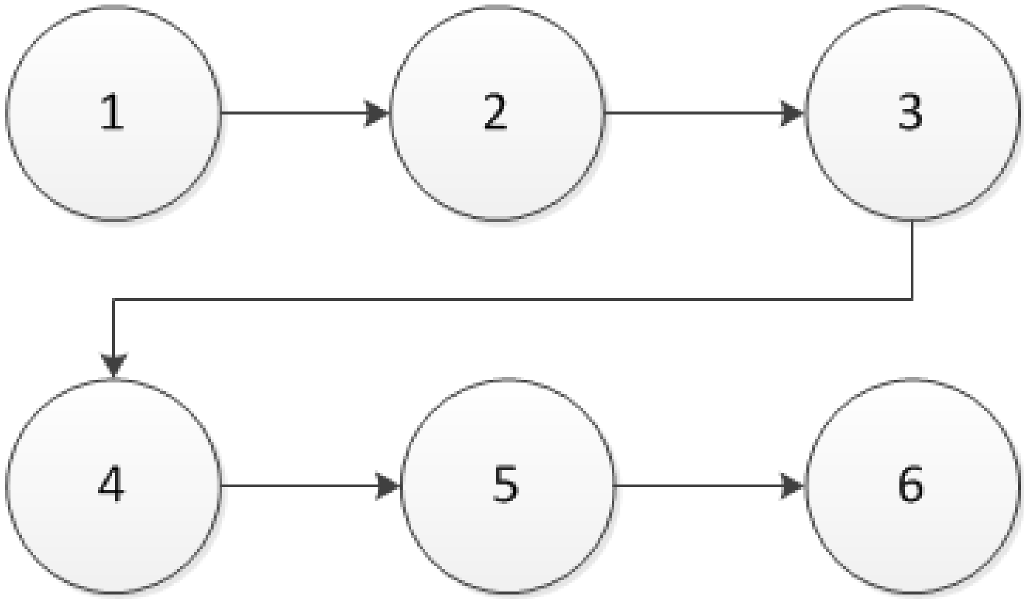

Figure 5.1: Work-flow with $N_s = 6$

The number of the workstation for each task can be calculated as

$$n_{ws,i} = \left\lceil \frac{\tau_i n_p V_i}{t} \right\rceil$$

where τ_i is the assembly time per part expressed in seconds, n_p refers to the number of parts per unit, V_i is the number of units assembled and t is the available time for assembly in the reference period.Theoretical time for production can be calculated as

$$t = w_p \cdot s_w \cdot h_s$$

where w_p are working week per year, s_w are the shifts per week and h_s hours of work per shift.

Another way to calculate n_{ws}, used in the implemented model,

$$n_{ws,i} = \left\lceil \frac{V_i}{t \cdot R_{p_i}} \right\rceil$$

where R_{p_i} is the productivity of the i-th workstation expressed in $parts/hour$.

If $N_{ws,i}$ is greater than 1, there will more than one workstation accomplishing the same task, working in parallel. It is necessary pointing out how the

production volume influenced the growth of total costs.
The assembly line can be balanced or not. An assembly line is not balanced when the work load, namely the assembly tasks, is not distributed to the workstation in the same quantity so the pace will be different. Balancing the line, splitting the workload among available workstations is one of the problem to face when the assembly plant during the design phase.
In a flexible automation environment the line is adapted to the product to assemble. Generally each task has a different cycle time when they are assigned to the workstations. Equipment is general purpose and it is able to run in the ranges of work that the designer established at the beginning. When new requirements come out, the plant needs to be adjusted and every workstation receive its workload. Likely this will not be exactly the same for all the task.
It is realistic to think that in a not dedicated line the efficiency of the balancing of the stations is not uniform and that, therefore, each of the workstations will have a different degree of saturation. From this it follows that with linearly increasing demand from time to time it will be to create a different bottleneck station, for which it is introduced a workstation in parallel.
Thus each workstation has a different cycle time, then likely it will fulfill the task earlier or later than one other workstation. Therefore with the grows of the demand, assuming same productive time, the number of workstation will not increase in the same pace if the demand increase gradually (e.g., linearly).
So the first step is to calculate the number of workstation according to the demand at every time step. It important to stress that in this research, the comparison is carried out counting only those costs that characterize a system rather than the other. It has been considered reasonable thinking that operations cost do not affect the decision and one might consider them as equals. This would have just complicated the model without adding any

useful information. Thus, the purpose of the comparison is to highlight the essential difference which lies in the way investment costs for the purchase of new workstations and costs of reconfiguration of the line occur.
Another already mentioned assumption is that, since it is not possible yet to quantify the cost of purchasing a EPS workstation, it is introduced a cost factor α, with $\alpha > 1$ in order to count that the cost expected of an EPS workstation higher than a FMS. This is another reasonable, not verifiable assumption, but it is consistent with the greater complexity of the structure of an evolvable workstation. More complex equipment would give rise to an higher cost. α is one of the parameters involved in the parametric analysis presented.
For comparison it is possible to express the direct costs $C_t^{(E)}$ for an EPS as follows (eq.5.1):

$$C_t^{(E)} = \sum_{t}^{t_n} \frac{\left[\left(\sum_{j=1}^{n_{pl}} f_{plj} C_{plj}\right) + \left(\sum_{i=1}^{n_{ws}} f_{ws_i} \alpha \cdot C_{wsi}^{F}\right) + C_p^{(E)}\right]_t}{(1+r)^t} \tag{5.1}$$

In the same way it is possible to express the cost of FMS system $C_t^{(F)}$,(eq.5.2): newline

$$C_t^{(F)} = \sum_{t}^{t_n} \frac{\left[\left(\sum_{i=1}^{n_{ws}} f_{ws} C_{wsi}^{F}\right) + C_p^{(F)} + C_h\right]_t}{(1+r)^t} \tag{5.2}$$

For every period within the time horizon one calculates the contribution of the two categories of terms.

5.1.2 Processes changes

For economical evaluation is important to take in account the dynamics of the system. Basically the analysis takes place within a unsteady state and it is not always possible to establish *a priori* what will be the evolution of the processes in the next generations.
In order to simulate the evolution of the processes within the life cycle of the plant it is presented an evolution model. The work-flow is composed by

tasks and each task needs a module to be accomplished.
Automatic workstations in evolvable paradigm domain, as well as in a flexible assembly system, are composed by machines that can perform a parametric process. Then, in case a process does not change in a work-flow and it remain similar to itself it is possible to reprogram such workstations and re-use it for similar production with a little effort in reprogramming. Reprogramming involves setting parameters (e.g., force applied, distance to cover and so forth) for the next production shift. It stands reason that the reconfiguration has a different impact on costs.
In order to count that, it is introduced an array of numbers $Q^{(r)}$ for each production shift.

$$Q^{(r)} = (q_1^{(r)}, q_2^{(r)}, q_3^{(r)}, \dots, q_k^{(r)})$$

$Q^{(r)}$ contains k components, with $k = N_s$, which is the number of processes involved in the r-th generation of production. [1].

If a process does not change over a production shift

$$q_i^{(r)} = 0$$

if it changes

$$q_i^{(r)} = 1$$

.

The number of changing process can be counted through the 1-norm of Q.

$$\|Q^{(r)}\|_1 = \sum_{i=1}^{k} q_i^{(r)}$$

in which each component represents a process to be performed relatively within the r-th cycle of production, namely the r-th generation.
$p_t^{(r)}$ *rate of evolution of the system* is defined as:

$$p_t = \frac{\|Q^{(r)}\|_1}{N_s}$$

[1] according to the assumption that each module accomplishes one process

Fluctuations of p_T mean that the number of process which change in the production shift increases or decreases.
If one consider N_g production shift, it is possible to define a matrix in which every row is a $Q^{(r)}$:

$$Q^{(r)} = (Q^{(1)}, Q^{(2)}, Q^{(3)}, \ldots, Q^{(r)})$$

Thus 1 means that the process change in the passage of next generation and 0 means that the focal process does not mutate.
If a process evolves it is necessary to provide a new equipment, if not the workstation does not change.

Reconfiguration cost in relation to number of changes for evolvable system is expressed as:

$$C_p^{(E)} = c_1 \cdot n_{ws}$$

being c_1 the cost for reconfiguring one workstation.

As aforementioned in Chapter 4, in case all the processes change it is necessary re-engineer the line ($p_t = 1$ for every production shift) so the cost grows with potence b.

$$C_{p,c}^{(F)} = c_2 \cdot n_{ws}^b$$

Reconfiguration cost for flexible, in case none of the processes change ($p_t = 0$ for every production shift), re-engineering of the system is not necessary and the cost for reconfiguration can be expressed as:

$$C_{p,nc}^{(F)} = c_3 \cdot n_{ws}$$

where c3 is the cost to reprogram one workstation.

In case some process change and same not, the relation has a linear contribution for unchanged workstations and cost which grows to the power of b for changing processes.

$$C_p^{(c)} = c_2 \cdot (p_t \cdot n_{ws})^b + c_3(1 - pt) \cdot n_{ws}$$

being n_{ws} the total number of workstations and c_2, c_3 respectively the cost for reprogramming each workstation or for re-engineering it.

5.2 MATLAB model

In a first time, an Excel spreadsheet was used to implement the cost model accordingly with scenarios proposed.
It was clear that this tool was not agile enough to fulfill a parametric analysis.
So it was decided to use another tool developed with MATLAB.
As depicted in fig5.2 as input, the user fill the number of process which compose the workflow N_s, the demand trends D, cost of workstations C_{ws}, number of production cycles N_g, the rate of interest r and the coefficient b. The script evaluates the number of workstation needed to process the required workflow according to the demand imposed. Afterwards using eq. 4.2, 4.3 it calculates the cumulated total costs over the production shifts.
At the end a graphic representation is presented.

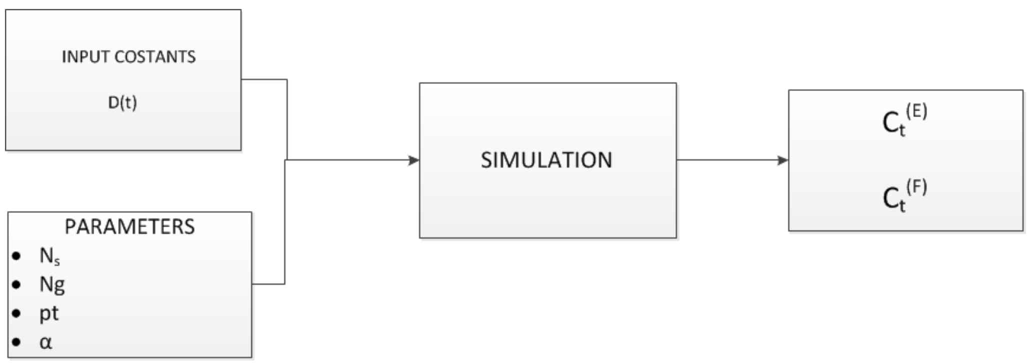

Figure 5.2: Block diagram of simulation script

5.3 Illustrative example

After having defined the model it is appropriate to propose an illustrative numerical example. It is speculated the trend of the costs of installation of an assembly system to perform a work-flow of $N_s = 6$ operations (fig. 5.1). It was therefore defined demand max for each generation of the product $D_{max} = 180000$ units.
This assunmption has been made:

- Each workstation performs a task.
- The production volume is deterministically defined with $D_{max} = 2000$ units per month, with two different levels of demand. In the first 6 month $D = 10000$ units per month.
- Available time for production=320 hours/month
- $C_{ws}^{(E)} = \alpha C_{ws}^{(F)}$

Before the system evolves over time, it will start at a certain level of demand, which refers to capabilities present during the introduction phase of a product. Starting with a large number of capabilities will reduce the likelihood for new equipment whether new requirements raise, avoiding new configuration costs and loss of time. Nevertheless oversized capacity means higher initial investment costs.An agile manufacturing system such EPS allows to dramatically reduce the effort with which new capabilities can be introduced to produce different varieties of products, despite the higher investment for purchasing equipment. In FMS environment as long as the working conditions are within preconceived requirements, namely they are inside the boundaries of flexibility, the system can easily shift from a production to another. Changing requirements beyond pre-established abilities imply hard work of adaption.

5.3.1 Scenarios

Considering the equation for calculation of cost

$$C_t^{(E)} = \sum_t^{t_n} \frac{\left[\left(\sum_{j=1}^{n_{pl}} f_{plj} C_{plj}\right) + \left(\sum_{i=1}^{n_{ws}} f_{ws_i} \alpha \cdot C_{wsi}^F\right) + C_p^{(E)}\right]_t}{(1+r)^t}$$

$$C_t^{(F)} = \sum_t^{t_n} \frac{\left[\left(\sum_{i=1}^{n_{ws}} f_{ws} C_{wsi}^F\right) + C_p^{(F)} + C_h\right]_t}{(1+r)^t}$$

It is set the productive demand trend over the period D(t). The parametric analysis has been carried out varying each time one of the following parameters:

N_s = number of tasks (steps)

N_g = number of production shifts (generations)

p_t = rate of evolution

α = factor cost

For each of the eleven instances has been made a graph where it is represented the trend of cost in both systems within lifespan of the plant.

Table 5.2 summarizes tests carried out on the comparative model. There are reported the established value for parameters.In tab.5.1 there are numerical value of the constants.

b	1.5
$C_w s$	20000 euro
R_p	60 parts/hour
t	320 hours/month

Table 5.1: Values of the numerical constants

Test	**Parameter**	**Value**
1.1	N_s	6
1.2	N_s	10
1.3	N_s	20
1.4	N_s	30
2.1	N_g	6
2.2	N_g	9
2.3	N_g	12
3.1	p_t	1
3.2	p_t	0
3.3	p_t	0.5
4	α	1.5; 2;2.5

Table 5.2: Overview of the numerical simulations scenarios

5.3.2 Test 1: N_s

The first series of tests involves the cost trend throughout 5 generations, assigning different values to the parameter N_s. In this dissertation, N_s is a qualitative representation of the complexity of the assembly system.
The first scenario with $N_s = 6$ is portrayed in fig. 5.3. The chart depicted shows that the costs for evolvable system are initially higher than flexible. This is consistent to the higher investment needed for evolvable workstations. During each production shift there is a reduction of the gap for EPS and FMS, until the curves intersect. After this moment EPS is more convenient than FMS.

Other three simulations (fig.5.4, 5.5, 5.6)have been carried out, each of one has higher number of tasks. It is possible to note how the point which makes the costs equal moves to the left, when the number of task is higher. This means that EPS discloses its convenience earlier with the increase of the processes. This is consistent with the assumption of the model: 'more

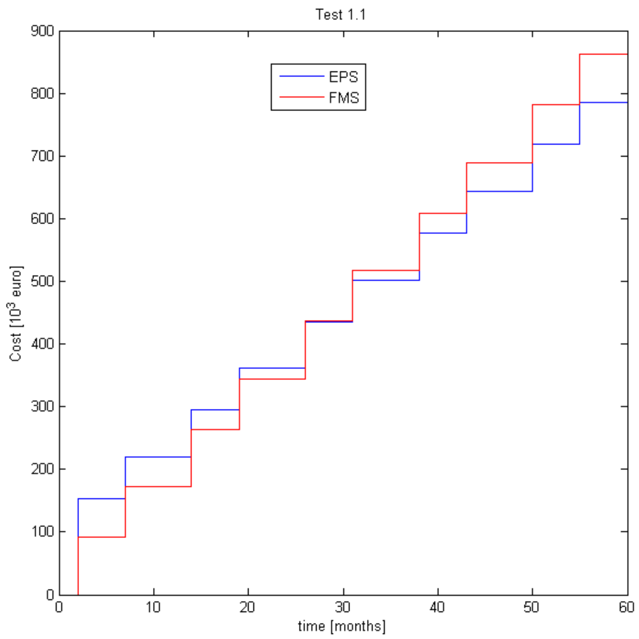

Figure 5.3: Test 1.1;$p_t = 1$, N_s=6, $N_g = 5$, $\alpha = 1.5$

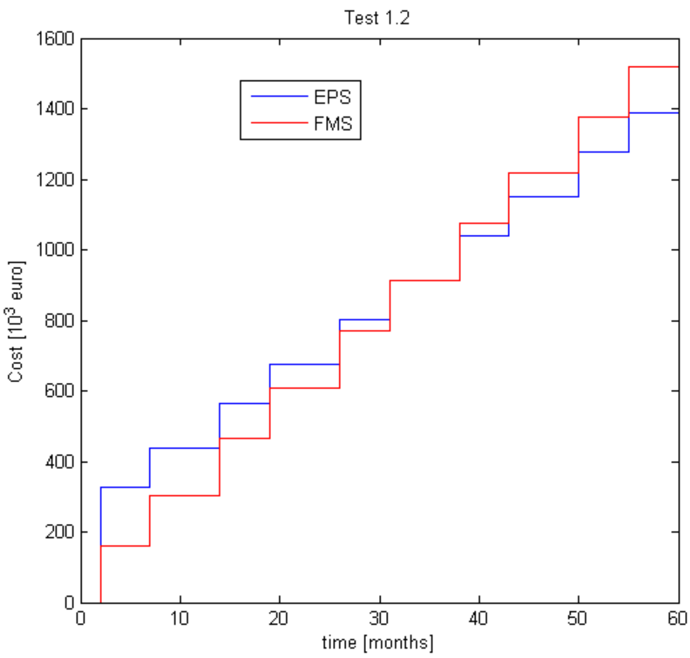

Figure 5.4: Test 1.2;$p_t = 1$, N_s=10, $N_g = 5$, $\alpha = 1.5$

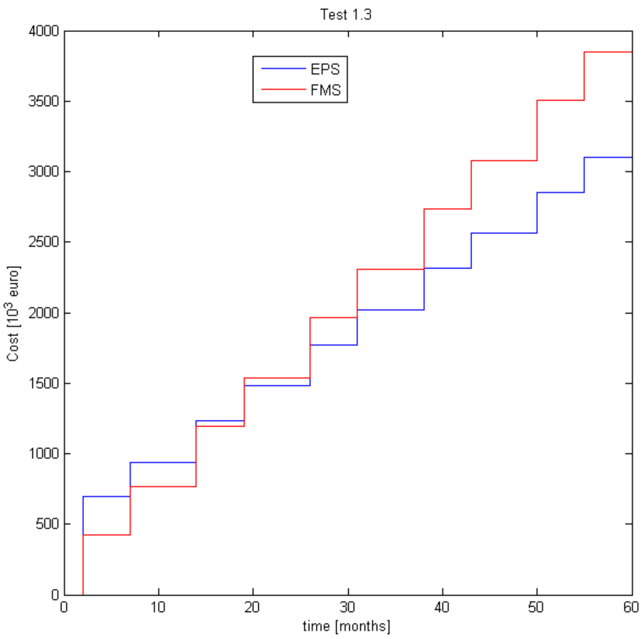

Figure 5.5: Test 1.3;$p_t = 1$, N_s=20, $N_g = 5$, $\alpha = 1.5$

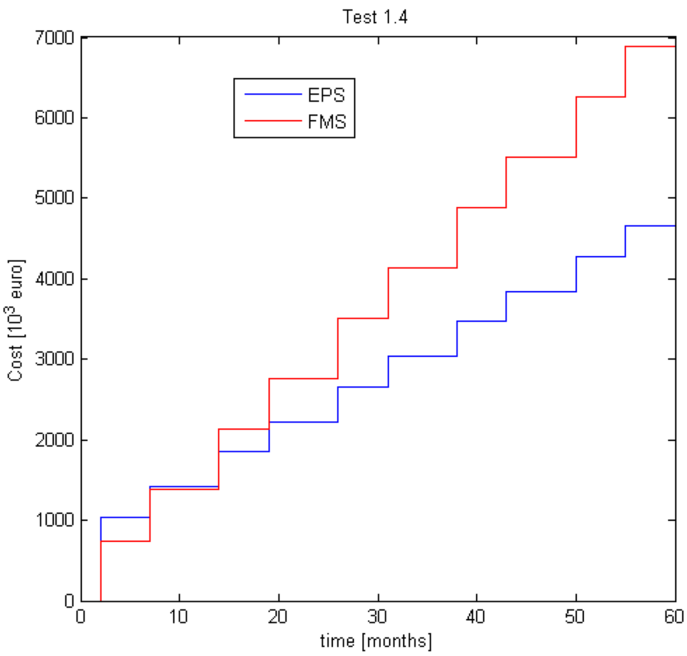

Figure 5.6: Test 1.4;$p_t = 1$, N_s=30, $N_g = 5$, $\alpha = 1.5$

tasks' means more workstations installed so more investment in equipment. This would seem to be an advantage for FMS, whose equipment is cheaper. However more stations also mean that re-engineering the assembly system will be more expensive. Summarizing in case of large number of workstations installed, EPS is the advantaged solution.

5.3.3 Test 2: N_g

The second parameter taken into account is the number of generations. Three test are carried out with growing number of generation shifts. The aim is to analyze the trend of costs within medium term period.
As one can see in fig.5.7 at the beginning the red curve is lower than the blue one. After two periods of time, as already happened for tests series 1, the curve intersect. From this point to the end of the time horizon EPS is more convenient.

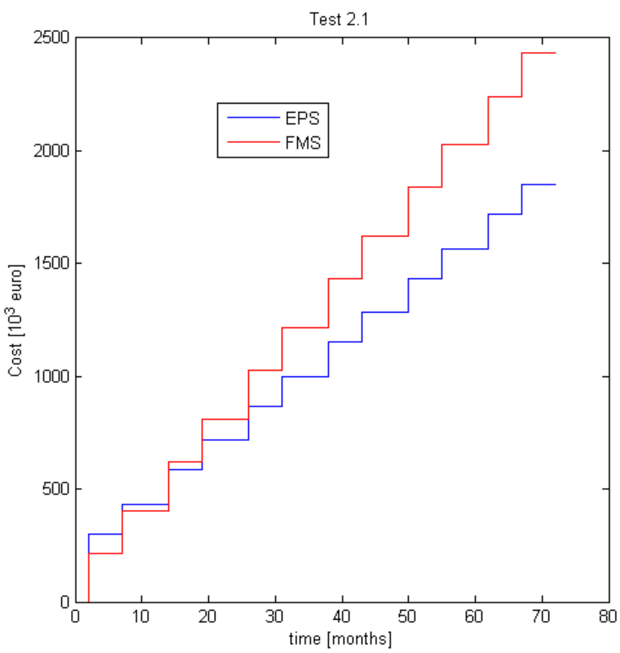

Figure 5.7: Test 2.1;$p_t = 1$, N_s=6,$N_g = 6$, $\alpha = 1.5$

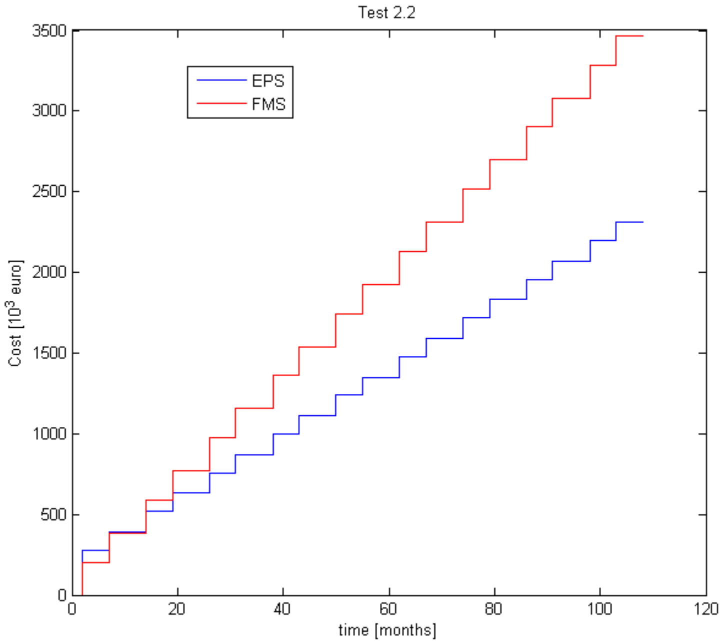

Figure 5.8: Test 2.2;$p_t = 1$, N_s=6,$N_g = 9$, $\alpha = 1.5$

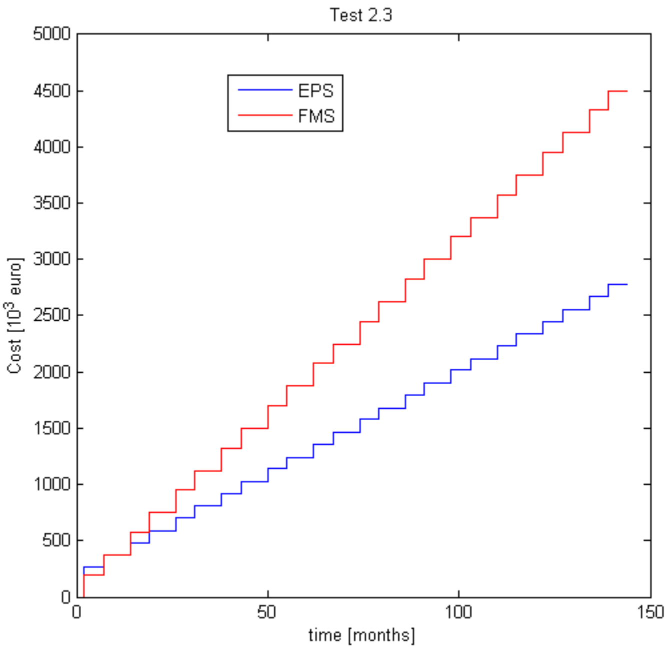

Figure 5.9: Test 2.3;$p_t = 1$, N_s=6, $N_g = 12$, $\alpha = 1.5$

Then with the growing number of generations FMS is definitely not convenient. This seems reasonable since every generation shift high cost for re-engineering flexible assembly system occur.
As delineated in fig. 5.8, fig 5.9 with the passing of generations, the gap between cost performance of EPS and FMS is growing more and more.
This is consistent with the expected trend.

5.3.4 Test 3: p_t

This series is definitely the most interesting one because of fluctuations of the process changing in the production shift.
It is fixed the same ev In the first scenario $p_t = 1$ (fig. 5.10), is a very turbulent one and it is possible to find the same trend already pointed out in previous scenarios.

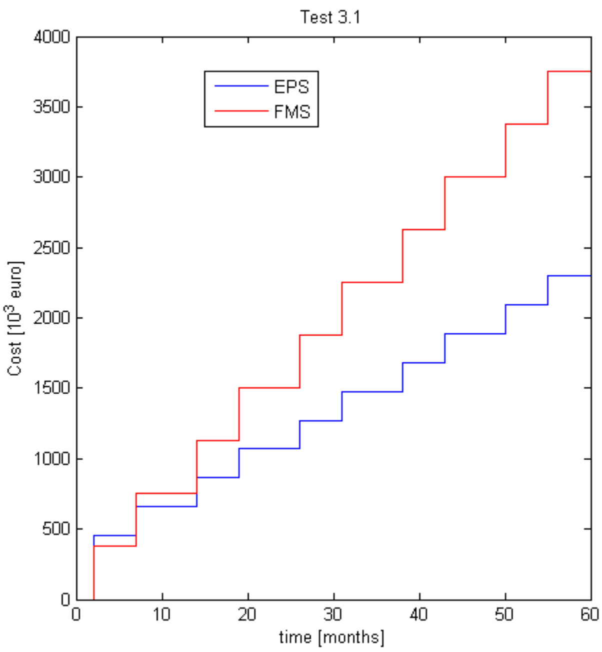

Figure 5.10: Test 3.1;$p_t = 1$, N_s=6 $N_g = 5$, $\alpha = 1.5$

The second case considered ($p_t = 0$) is more interesting and depicts a quite stable scenario in which the product change but the processes remain similar to themselves. This simulation puts in evidence the peculiar feature of flexible automation. If requirements do not change, one can easily reprogram the workstation, exploiting flexibility, as shown in (fig.5.11). In this way one takes advantage of the flexibility of FMS system. Indeed if one remain inside the ranges of flexibility established during the design phase. This makes the FMS system cheaper than EPS.

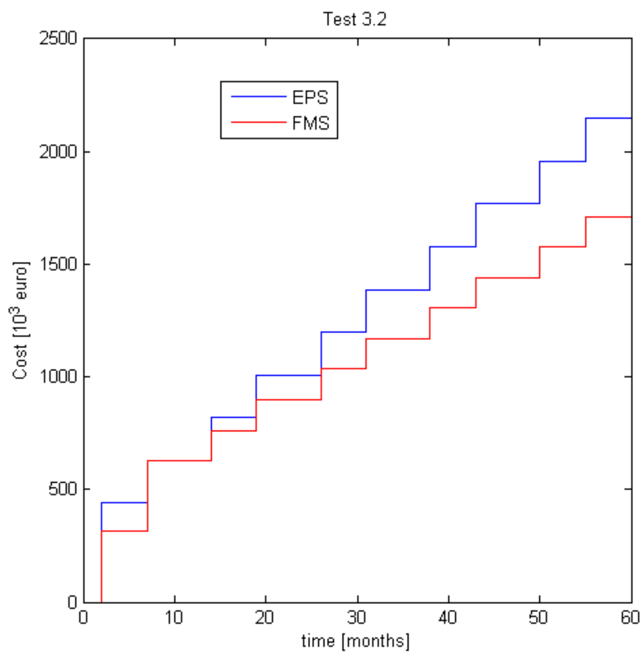

Figure 5.11: Test 3.2;$p_t = 0$, N_s=6 $N_g = 5$, $\alpha = 1.5$

The third scenario presented is the one with $p_t = 0.5$ (fig.5.12). If just some processes change and some remain similar, there is an intermediate condition. In this case total costs are similar, with the FMS which seems to be cheaper. Since in this simulation the two curves are closer than in other cases, it is useful going deeply and trying to vary also α.

5.3.5 Test 4: α

The fourth simulation aims to determine which is the threshold value for the cost factor α. α is the ratio $\frac{C_{ws}^{(F)}}{C_{ws}^{(E)}}$. One wants to determine the maximum value that can take alpha in both cases so that the alternatives are equivalent. Then it it is presented how the cost of the evolvable workstation affects the total cost. For this we repeat the calculation of costs with $1.5 \leq \alpha \leq 2.5$. In fig. 5.13 one can see four curves: the three blue ones shows the trend of costs for EPS with $\alpha = 1.5$,$\alpha = 2$,$\alpha = 2.5$; the red one represented the FMS cost as it has been done previously.

It is possible to note that when $\alpha = 2$ the cost of FMS and EPS are similar. In the other two cases, with $\alpha = 1.5$ EPS is more convenient, whereas whit $\alpha = 2.5$ the evolvable workstations' cost it too high to be balanced from the lower reconfiguration costs.
Summarizing EPS , as it is shown within first series of test, the more the system is complex the more the EPS becomes convenient. Complexity in this work means more task to perform, then more workstation to configure and re-engineer in case of change of product requirements. Similar trends have been found with the increase of product shift during the second series of tests: more production shift, mean more adjustments of the system then increasing cost for FMS, even in this case EPS seems to have better performance.
The third series of test put in evidence the peculiar attitude of flexible systems to have good performance if the line does not work outside its flexibility ranges.
Finally forth series put in evidence, that even if the cost of the evolvable workstation will be twice the actual cost of flexible equipment, the system keep cost effectiveness.

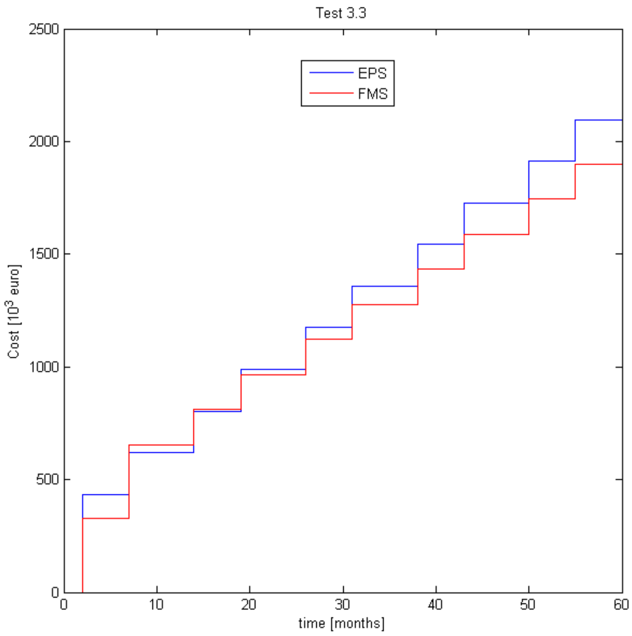

Figure 5.12: Test 3.3;$p_t = 0.5$, N_s=6 $N_g = 5$, $\alpha = 1.5$

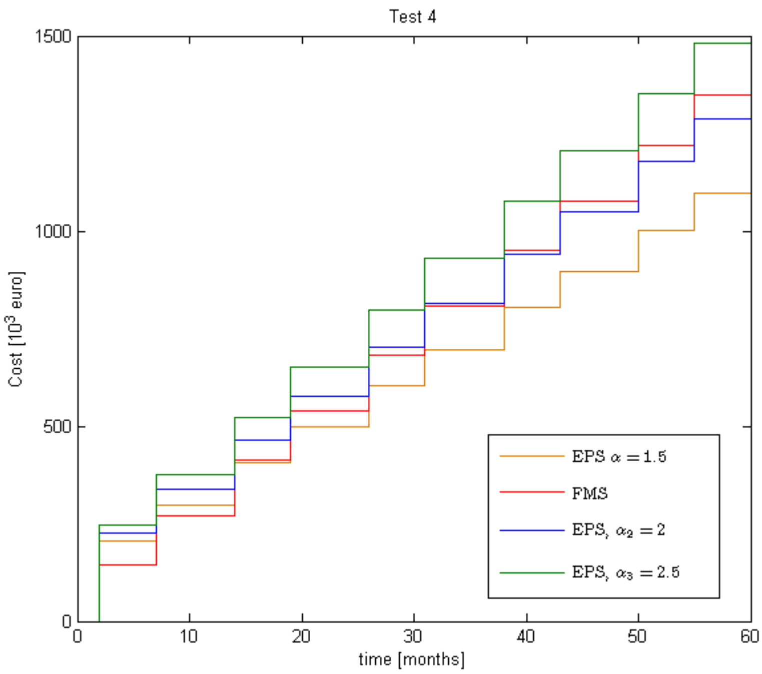

Figure 5.13: Test 4;$p_t = 0.5$, N_s=6 $N_g = 5$, $\alpha_1 = 1.5$,$\alpha_2 = 2.05$,$\alpha_3 = 2.5$

Chapter 6

Conclusion and future work

6.1 Conclusions

The proposed model and the comparative analysis carried out are first steps in the built of a costing methodology to evaluate the economical impact of evolvable production systems.
The model confirmed the initial hypothesis of the EPS to be able to maintain the low cost of ownership for productions with several changes of generation thanks to its modularity, agility and easy configurability.
The comparison highlighted that evolvability paradigm is scarcely affected from the rate of processes changing. On the contrary the flexible assembly system results to be really sensitive to the rate of evolution.
As any other model the value of the results is valid within the depicted domain and it is affected by the declared assumptions.
The illustrative example, as well as the model, is considered valid with the assigned values.
Thus, the proposed model is useful to highlight what is the main difference between the evolvable and flexible paradigms. The purpose of this work was not to provide a calculation tool, but to indicate a way to describe significant costs directly connected to an installation and the use of an automatic assembly system.

Furthermore it must be stressed that, while flexible systems are an established industrial reality the paradigm of evolvability is still at an early stage of its development, and currently it is still not available in the industrial automation market. Nowadays there are some demonstrator systems developed by IDEAS, but none of them is working on real productions.

6.2 Future Work

It is suggested as a natural development of this work, the study of the costs of a flexible assembly plant already built, comparing them with those of demonstration plants EPS available to the consortium IDEAS.
Probably the developing of a complete cost model for such a complex system requires a deeper analysis with more appropriate mathematical tools.
One of the further developments of this work can be the study of systems considering stochastic demand and not just deterministic. In that way one can handle uncertainty.
The ultimate goal of the research could be the implementation of a complex configurator software tool for calculating the costs of the system to be incorporated into Multi Agent System to support the choices of the system. From the available modules, the system may choose the most appropriate combinations flanking the technical considerations on the compatibility of the modules most appropriate, the costs for the definition of the most suitable technically and economically cheaper solution.
In order to deepen the evaluation of investment considering all the firm framework, a multiple-objective decision model should be developed. This come from the need to quantify flexibility and self-configurability in a better way. As seen previously there are some example available in literature.

Appendix A

MATLAB code

In this appendix is reported an example of the model developed in MATLAB.

```
%%%%%%%%%%%%%%%%%%  COST COMPARISON SIMULATION %%%%%%%%%%%%%%%%%%%
clc
clear all
close all
%%%%%%%%%%%%%%%%% INPUT %%%%%%%%%%%%%%%%%%
%  PARAMETERS

Ns=10;
Ng=5;
a=2.5;    %%this is alpha

%%COSTANTS
%for a=1:0.5:2;
%a=Cws_e/Cws_f

b=1.5;
Cpl = 14;    %cost of the modular platform
CwsF=20;    %Cost of each flexible workstation
```

```
%operating unit cost (supposed to be variable cost,
Cvue=2*10^(-4)*0;
Cvuf=2*10^(-4)*0;
C1=3;     %configuration unit cost EPS
C2=4;     %engineering per unit cost FMS
C3=14;     %configuration unit cost FMS

%for Ns = 10:10:30; % numero di step nel processo produttivo

Vmax=20000;   %number of units

%V1=1*[1000:10000:Vmax]'; % andamento della produttività target

V1= [0.5*Vmax*ones(6,1);Vmax*ones(6,1)];
V2=1.2*Vmax*ones(12,1);    % each volume
V3=1.4*Vmax*ones(12,1);
V4=1.5*Vmax*ones(12,1);
V5=2*Vmax*ones(12,1);

V3=V2;
V4=V3;
V5=V4;
%V=[V1;V2;V3;V4;V5];
%V=[V1;V2;V3;V4;V5;V4;V3;V2;V4;V5;V1;V2;V3];
V=[V1;V2;V3;V4;V5;V4;V3;V2;V4;V5;V1;V2;V2;V2;V2];    %%Demand vector
Nt = length(V1);
Te = 320; %
%tempo dedicato alla produzione (6 mesi per generazione)

% Production rate for each process in the workflow for EVOLVABLE SYSTEM
```

```
Rpe = 5*[10 11 7 10.5 9 11 8.5 9.5 8.8 10.5]
% Production rate for each process in the workflow for FLEXIBLE SYSTEM
Rpf = 5*[10 11 7 10.5 9 11 8.5 9.5 8.8 10.5];
comp=Ns; % COMPATIBILITA' dei processi

%SNws = zeros(Nt,Ns,Ng); % registro del numero di stazioni
% registri dei costi

Ce = zeros(Nt,Ng);    %Total Cost EPS
Cf = zeros(Nt,Ng);    %Total Cost FMS
%row=number of volumes step, column number of generations
tf=Nt;
enne=tf*Ng/12;
time=[1:tf*Ng]';   %Time Mesh
z=zeros(Ns,1)';
Q=zeros(Ng,Ns);
o=ones(Ns,1)';
p1=[1 0 0 0 0 0 0 0 0 0];
p2=[1 1 0 0 0 0 0 0 0 0];
p3=[1 1 1 0 0 0 0 0 0 0];
p4=[1 1 1 1 0 0 0 0 0 0];
p5=[1 1 1 1 1 0 0 0 0 0];
p6=[1 1 1 1 1 1 0 0 0 0];

%Matrix of process changing
Q=[o;o;o;o;o;o;o;o;o;o;o;o;o;o;o;o;o;o;o;o;o];   % depending on p_t
%Q=[z;z;z;z;z;z;z;z;z;z;z;z;z;z;z];
Q=[p5;p5;p5;p5;p5;p5];
% Q=[o;z;o;z;o;z;z;o;z;z;o;z;z;o;z];
%Q=[o;p1;p1;p1;p1;p1;p1;p5;p1];
```

```
%Q=[o;p5;p5;p5;p5];

r=0.3/12;  %rate of interest
% annual fraction of the cost of the platform that
%must be allocated on the focal EPS
f=((r*(r+1)^enne)/((r+1)^enne-1));

%% %%%%%%%%%%%%% RUN SIMULATION %%%%%%%%%%%%%%%%%%%%
%Nws=[];
Cep=12*Ns;
Cfp=7*Ns;
CVe=0; %Variable cost   EPS
CVf=0; %Variable cost FMS
CV=[];

for l=1:Ng  % Generations

norma(l)=norm(Q(l,:),1);
for i=2:Nt   % Volume

for j=1:Ns   %Steps
%number of workstation needed EPS
Nwse(i,j) = ceil(V(i)/(Te*Rpe(j)));
%number of workstation needed FMS
Nwsf(i,j) = ceil(V(i)/(Te*Rpf(j)));

Nwse_buff(i,j)=Nwse(i,j);
Nwsf_buff(i,j)=Nwsf(i,j);

Nws_buff_e=sum(Nwse_buff,2);
```

```
Nws_buff_f=sum(Nwsf_buff,2);

%Nwse(i,j)=Q(l,j).*Nwse(i,j);
%Nwsf(i,j)=Q(l,j).*Nwsf(i,j);
% else
% Nwse(i,j)=0;
% Nwsf(i,j)=0;
% end
Nws_step_e=sum(Nwse,2);
Nws_step_f=sum(Nwsf,2);


%Number of new worksation needed for each step
delta_ws_e(i)=(Nws_step_e(i)-Nws_step_e(i-1));
delta_ws_f(i)=(Nws_step_f(i)-Nws_step_f(i-1));


d_e=Nws_buff_e(i)-Nws_buff_e(i-1);
d_f=(Nws_buff_f(i)-Nws_buff_f(i-1));


%rate of evolution p_t here has been called ev
ev(l)=(norma(l)/Ns);
% nev=(1-ev)
nev(l)=(1-norma(l)/Ns);


%Cost for EPS
Ce(i,l)=(((f*Cpl*ceil(delta_ws_e(i)/6)+f*a*CwsF*(delta_ws_e(i))+
(d_e)*C1+CVe(i)))/((1+r)^time(i)))+Cep;
```

```
%Cost for FMS
Cf(i,l)=((f*(CwsF*(delta_ws_f(i)))+(d_f*ev(l))*C3+(d_f*nev(l)*C2)+
CVf(i))/((1+r)^time(i)))+Cfp;

end

Cep=Ce(i,l);
Cfp=Cf(i,l);
CVe(i,l)=CVe(i);
CVf(i,l)=CVf(i);
Ce(1,i)=Ce(Nt,i-1);
Cf(1,i)=Cf(Nt,i-1);
end

%Ce_max(l)=max(Ce(i,l));
end
nt=length(Ce_max);
t_step=linspace(1,nt,nt);

%% vector of cost for EPS
%Ct_e=[Ce(:,1);Ce(:,2);Ce(:,3);Ce(:,4);Ce(:,5);Ce(:,6)
 %Ce(:,7);Ce(:,8);Ce(:,9)];%Ce(:,10)];

%% vector of cost for FMS
%Ct_f=[Cf(:,1);Cf(:,2);Cf(:,3);Cf(:,4);Cf(:,5);Cf(:,6)
 %Cf(:,7);Cf(:,8);Cf(:,9)]; %Cf(:,10)];


%% %%%%%%%%%%%%%%%%%%%% PLOT THE RESULTS %%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
figure(1)
stairs(time,Ct_e)
%plot(time(2:diff),Ct_e(2,:))
hold on
% end
stairs(time,Ct_f,'r')
%plot(time(2:diff),Ct_f(2,:),'r')
% grid on
hold on
title('Test 4')
legend('EPS','FMS','Location','NorthEastOutside')
xlabel('time [months]')
% plot(time,V,'k')
ylabel('Cost [10^3 euro]')
%end
```

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