# POLITECNICO DI MILANO

School of Industrial and Information Engineering

Master of Science in Mechanical Engineering

Bovisa Campus

# TITLE: Introducing Modularity as enabler for circular economy of automated assembly lines

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Academic Year 2020-2021

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# Abstract

The concept of circular economy (CE), in which a product is reused after a lifecycle is completed, is becoming more and more important due to resource scarcity and to reduce waste and pollution; therefore, manufacturers need to adapt and develop new business models (BM) to cope with this trend. In this regard, Pay-Per-Use (PPU) is a business model that embraces the concept of CE: the product is no more sold to the customer, but it is the production capacity of the product that is sold as a service. This implies that the client uses the product for a limited period, after which the product will be recollected by the producer. In this context, this thesis deals with the implementation of this BM in manufacturing industry, more specifically in the assembly machines industry. Different aspects must be considered to properly implement this new BM, the first one is related to the impacts that this approach brings to manufacturers, the implementation increases the flow of information between different functions inside company and increases the interactions with the client, but as advantage it reduces the time to market and the reconfiguration time. To properly explain the modifications that this BM brings to companies, an IDEF scheme that explains the flow of information and materials is reported in this work. The other important aspect that must be considered is related to the architecture design of the product that must be easily reconfigurable because it will be used for different purposes by different customers. To allow that, modularity and standardization are two key concepts that must be developed, thus the assembly lines will be composed by different units, the modules, that can be composed to build the final product. Due to introduction of this new product architecture, the configuration process of the product will be impacted and modified. In this work the steps required to configure a modular assembly line suitable for PPU are explained. To properly explain this procedure and to validate it, a real case scenario is analysed considering an Italian SME that produces automated assembly lines.

**Keywords: Pay-per-use, circular economy, assembly lines, reconfigurable manufacturing system, modularity, configuration of modular assembly line.**

# Sommario

Il concetto di economia circolare (CE), in cui un prodotto viene riutilizzato una volta che il suo ciclo di vita è concluso, sta diventando sempre più importante a causa della scarsità di risorse e per ridurre sprechi e inquinamento; pertanto, le aziende devono adattarsi e devono sviluppare nuovi business models (BM) per affrontare questa tendenza. A questo proposito, Pay-Per-Use (PPU) è un business model che considera il concetto di CE: il prodotto non viene più venduto al cliente, ma è la capacità produttiva ottenuta dallo stesso che viene venduta come un servizio. Questo implica che il cliente usi il prodotto per un periodo limitato, dopo il quale viene riconsegnato al produttore. In questo contesto, questa tesi tratta l'implementazione di questo BM nel settore della produzione industriale, nello specifico nella produzione di linee di assemblaggio. Diversi aspetti devono essere considerati per implementare questo BM, il primo è relativo agli impatti che questo approccio possa portare ai produttori, l'implementazione aumenta le interazioni con il cliente, ma come vantaggio riduce il time to market e il tempo necessario per la riconfigurazione del prodotto. Per spiegare in maniera esaustiva le modifiche che questo BM possa portare alle aziende, uno schema IDEF che spieghi il flusso di informazioni e di materiali è riportato in questo lavoro. L'altro aspetto fondamentale che deve essere considerato è relativo al design dell'architettura del prodotto che deve essere facilmente riconfigurato poiché verrà usato per scopi differenti da clienti differenti. Per permettere questo, modularità e standardizzazione sono due concetti chiave che devono essere sviluppati; pertanto, le linee di assemblaggio saranno composte da diverse unità fondamentali, i moduli, che possono essere composti per costruire il prodotto finale. A causa dell'introduzione di questa nuova architettura del prodotto, il processo di configurazione del prodotto sarà impattato e modificato. In questa tesi, i passaggi richiesti per configurare una linea di assemblaggio modulare che sia adatta per il PPU sono spiegati. Per spiegare questa procedura e per validarla, un caso reale è analizzato considerando un'azienda italiana che produce linee di assemblaggio automatizzate.

**Parole chiave: Pay-per-use, economia circolare. Linee di assemblaggio, sistema di produzione riconfigurabile, modularità, configurazione di linea di assemblaggio modulare.**

# Chapter 1 - Introduction

The limited availability of resources present on planet Earth is drastically increasing and primary materials consumption is expected to double, reaching 167 gigatonnes in 2060. Indeed, to pursue more sustainable development, different countermeasures have been proposed to identify new and sustainable strategies to run systems.

These new trends strongly impact not only on consumers' behaviour but also on industrial actors among which manufacturers, that are required to move towards economic, environmental, and social sustainability [1].

To pursue this goal, one of the most promising paradigms recently identified is Circular Economy (CE).
CE is defined as "an industrial economy that is restorative and regenerative by intention and design, and it relies on three principles: (i) preserve and enhance natural capital, (ii) optimize resource yields and (iii) foster systems effectiveness" (The Ellen MacArthur foundation, 2015).
The most relevant aspect is related to the fact that in CE the production is circular, this implies that products are reused in successive production cycles.

To be competitive and ready for future challenges, companies need to adapt to this trend, to do that they must change their business organization, thus they must change their business model.
The change toward a CE based business model affects many different functions inside companies at different levels, from after sales department to design department.

The scope of the work is to analyse how manufacturing firms will change their business model towards a specific CE based business model that is Pay-Per-Use (PPU).

In a pay-per-use scheme, the customer does not pay for the purchase of the product because he does not own the product, by contrast the customer pays a fee that is based on the level of consumption of the product itself.
Therefore, the product remains property of the manufacturer that sells a service (i.e. a production capacity) and he must recover the functionality of the product after a life cycle is completed.
This scheme implies strong difficulties and novelties in many different aspects, from architecture design to management of machinery.

The core of this work will be related to design modifications of the products, that must be easily reconfigured to be used for different purposes or different clients, in different moments.

A system is defined reconfigurable when its layout can be easily changed and the most effective way to do that is by exploiting a modular design.

Modularity allows easy reconfiguration of machines and standardization of components through the composition of basic building blocks: the modules.

This new architecture design of production system introduces a new challenge that is related to the configuration of machines that must be properly configured.

This work is interested in the definition of an automatic and repeatable approach to configure assembly systems starting from a new request by a client.

Moreover, a real case study is provided to understand the practical implications of this shift toward this innovative business model.
The company under investigation is COSBERG S.p.a. that is a small-medium firm located in Lombardy that produces highly automated assembly machines.
This company is suitable for this analysis because they are already working on different aspects related to the concept of CE, in fact they are already working on the modularization of their machines.

The work is organized as follows:

- in **Chapter 2** the topics related to circular economy are explained with a focus on Pay-Per-Use. Related to that, the concepts of reconfigurable manufacturing systems and modularity are discussed.
- in **Chapter 3** a state-of-the-art overview of all the functions needed to implement a PPU business model are discussed, an IDEF, that describes the overall functioning of a company once a PPU business model is implemented, is presented. Moreover, a focus on machine architecture design and automatic machine configuration is considered.
- in **Chapter 4** the real case scenario is introduced with a comprehensive explanation of the company analysed: Cosberg S.p.a.
- in **Chapter 5** the real case study is presented, and the methodology explained in chapter 3 is developed considering different assembly lines produced by Cosberg S.p.a.
  The configuration and the reconfiguration of the lines is presented and explained.
- in **Chapter 6** conclusions are presented, as well as future possible developments.

# Chapter 2 - Literature review

In this chapter, the basic concepts required to properly understand the topics discussed in the work are presented and explained.

The literature has been analysed to select the most relevant papers and four main keywords have been used to filter the search: circular economy, pay-per-use, reconfigurable manufacturing systems and modularity.

## 2.1 Circular economy

The impact that industrial business has on the environment is a topic of huge interest and an increasing pressure on companies is rising. The main concern is related to pollution and waste, but also the challenge of resource scarcity in a continuously expanding market must be taken into consideration.
As a matter of fact, the demand of raw materials is constantly increasing while the supply of crucial materials is limited. In addition, extracting and using raw materials has a major impact on the environment due to energy consumption and CO2 emissions.

Linear economy, i.e. take-make-use-dispose, is showing its limits because it does not take into consideration environmental factors, the public opinion, new pollution regulations and resource scarcity.
In fact, the concept of linear economy is considered no more sustainable because the resources present on planet earth are constantly decreasing while the waste produced is constantly increasing.

In the light of the above-mentioned problems, the concept of circular economy (CE) is considered as a solution for harmonizing ambitions for economic growth and environmental protection. [2]

The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended.
In practice, it implies reducing waste to a minimum, in fact when a product reaches the end of its life, its materials are kept within the economy wherever possible. These can be productively used again and again, thereby creating further value. (European Commission)

CE is understood as "realization of closed loop material flow in the whole economic system" (Geng and Dobertein, 2008), this means that producers take back their products after use and repair and restore them for a new useful life as shown in the figure:

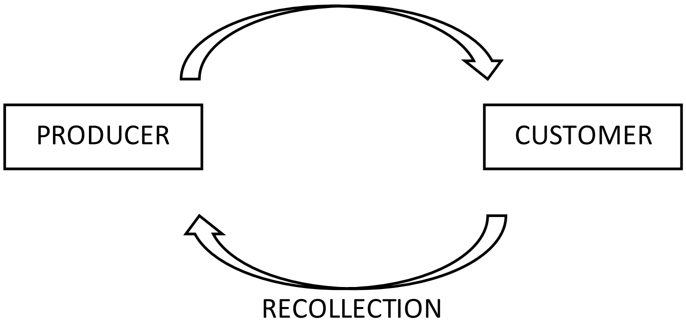


*Figure 1: CE principle*

There are 3 main principles that can synthetise the concept of CE, the so-called 3R:

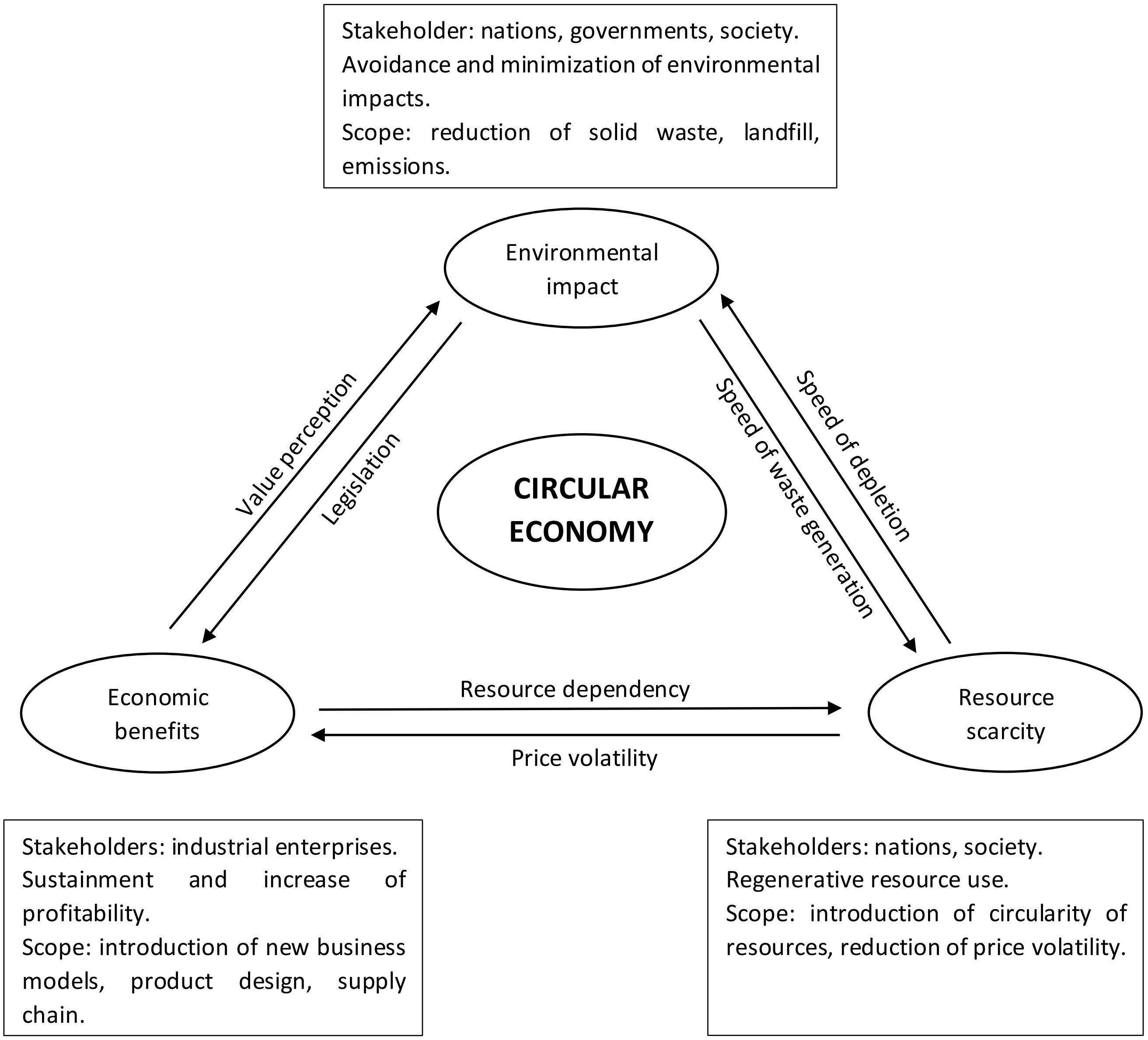
- Reduce, both raw materials and structural waste.
- Reuse of product directly at the end of its life cycle
- Recycle of finished goods through transformation processes (like remanufacturing).

Not only environmental factors have to be considered however, CE has also positive impact on economic factors, in fact is defined as “an industrial economy that is restorative or regenerative by intention and design” (Ellen Macarthur Foundation, 2003). This is related to the fact that resources are fully exploited during several life cycles, thus there is an increase of resource efficiency.

Therefore, the CE approach appears not only apposite but also inevitable to respond to challenges of resource scarcity, environmental impact or economic benefits or combinations of these. [2]

All these factors can be put together to obtain a comprehensive CE framework [2] that helps to understand which is the logic and the advantages behind this new rising trend.

The framework is shown in the figure:



Stakeholder: nations, governments, society. Avoidance and minimization of environmental impacts. Scope: reduction of solid waste, landfill, emissions.

Stakeholders: industrial enterprises. Sustainment and increase of profitability. Scope: introduction of new business models, product design, supply chain.

Stakeholders: nations, society. Regenerative resource use. Scope: introduction of circularity of resources, reduction of price volatility.

*Figure 2: CE framework*

The above-mentioned framework can be adopted at different scales: the micro one that corresponds to products and firms view, the meso one corresponding to a network of companies, and macro one that corresponds to actions undertaken by cities, regions, and nations.
CE principles adoption are promising especially for manufacturers to reduce material consumption and resource toxicity while carrying on their business activities. [1]

Considering the highlighted characteristics, the benefits of CE can be summarized as:

- Waste prevention.
- Ecodesign and reuse that can reduce total greenhouse gas emission.
- Reducing pressure on the environment.
- Improving the security of the supply of raw materials.
- Increasing competitiveness.

- Stimulating innovation.
- Boosting economic growth (an additional 0.5% of gross domestic product).
- Creating jobs (700.000 jobs in the EU alone by 2030). [European Parliament]

### 2.1.1 Circular economy action plan (CEAP)

CE adoption has been promoted by policymakers through the recent action plan (European Commission, 2020).

The European Commission adopted the new circular economy action plan (CEAP) in March 2020. It is one of the main building blocks of the European Green Deal, Europe's new agenda for sustainable growth. The EU's transition to a circular economy will reduce pressure on natural resources and will create sustainable growth and jobs. It is also a prerequisite to achieve the EU's 2050 climate neutrality target and to halt biodiversity loss.

The new action plan announces initiatives along the entire life cycle of products. It targets how products are designed, promotes circular economy processes, encourages sustainable consumption, and aims to ensure that waste is prevented, and the resources used are kept in the EU economy for as long as possible.

The Circular Economy Action Plan aimed to cover the full economic cycle — from production to consumption, repair and remanufacturing, to waste management and secondary raw materials. It encompasses a variety of material flows: plastics, food, critical raw materials, construction and demolition, and biomass and bio-based materials. Cross-cutting measures to support this systemic change through innovation and investments were also put in place.

To promote innovation, send a signal to the market, and support the industrial sector's transition to a circular economy, more than EUR 10 billion of public funding was put forward between 2016 and 2020. Circular economy innovation funding came from several EU programmes, including Horizon 2020, the Cohesion Policy, the European Fund for Strategic Investments, Innovfin, and LIFE. For instance, EUR 1.8 billion of Cohesion Policy funding was provided to SMEs for the uptake of eco-innovative technologies, and at least EUR 100 million went to more than 80 circular economy projects through LIFE funding.

The EU's Circular Economy Action Plan has had an impact on several policy areas and across the economy. A couple of indicators show that part of the European economy is becoming more circular. For instance, according to Eurostat, circular activities such as repair, reuse, and recycling generated almost EUR 155 billion in value-added in 2017. There was also a 6% increase in jobs related to the circular economy between 2012 and 2016. The EU's overall circularity rate, the percentage of recovered and recycled materials used in production, increased from 3.4% to 11.7% between 2004 and 2016. However, these increases cannot be solely attributed to the adoption of circular policies as there are other factors to take into consideration. Also, the role of Member States, regions, and cities in implementing circular initiatives must be accounted for.

To encourage a more holistic approach to design, the Ecodesign Working Plan 2016-2019 extended the scope of ecodesign requirements beyond energy efficiency. These new requirements aimed to consider the whole life cycle of products and materials. By introducing material efficiency requirements on several products, the working plan promoted reparability, upgradeability, durability, and recyclability of consumer goods. The European Standardisation Organisations are responsible for developing criteria to measure the circularity of a product and the presence of critical raw materials. These new criteria will be applied in existing and new standards.

To promote the transition across Europe, policymakers at all levels of governance were encouraged to implement circular economy strategies. Since 2016, at least 14 Member States, eight regions, and 11 cities have put forward a circular economy strategy. While some countries such as France and certain regions, such as Catalonia and Flanders have adopted long-term circular strategies, others such as the federal governments of Belgium and Germany have opted for more short-term circular initiatives. Some of the frontrunners are introducing regulations which go beyond the EU requirements. For instance, the Netherlands aims to reduce its use of primary raw materials by 50% in five economic sectors by 2030. Furthermore, France has adopted an anti-waste law for the circular economy in early 2020, which bans the destruction of unsold goods, encourages donations, and fosters secondary markets. However, in several other Member States the understanding of a circular economy remains low, particularly outside of environment ministries in the national capitals. [Ellen MacArthur Foundation, 2020]

## 2.1.2 Enablers of circular economy

Technologies are considered by researchers one of the most important aspect to boost sustainable development, especially for CE adoption.

Digital technologies (DTs), such as the Internet of Things (IoT), big data, and data analytics, represent essential enablers of the circular economy (CE). Therefore, the continuous development of these technologies will help and will be fundamental for the growth of CE based industries.

DTs, in fact, can be used for tracking the flow of products, components, and materials and making the resultant data available for improved resource management and decision making across different stages of the industry life cycle. Moreover, data analytics can serve as a tool to predict product health and wear, reduce production downtime, schedule maintenance, order spare parts, and optimize energy consumption. [3]

As an example, a company can implement a monitoring system on their products made of sensors that are connected via internet to a database that collects all the data. Thus, the company can remotely analyse these data to increase efficiency of a product or to understand the wear of a specified component that will be repaired before the delivery to another customer (i.e. introduction of preventive maintenance).

Therefore, effectively using this digital transformation will be pivotal for organizations in transitioning to, and leveraging, the CE at scale. [3]

There are other 2 technologies that are extremely useful for manufacturers that want to follow this trend of CE, they are: regenerative design and remanufacturing.

Product design is identified as crucial element in the development of circular system, in connection with critical material research. To succeed, companies need to adapt the design of their product that must be specifically realised to follow this trend of reuse.
Longer-lasting materials can be adopted to reduce wear or processes can be introduced to increase life of components. In addition to that, the architecture of products must be specifically engineered for fast modifications and maintenance, in fact a product that cannot be modified for different customers or that cannot be easily repaired is not suitable for a CE based business.

Moreover, the recovery of products and the extension of their lives is driven by remanufacturing that is linked to the before-mentioned design of products. Key steps for remanufacturing are disassembly, cleaning, inspection, and sorting, reconditioning and reassembly. [2]
Remanufacturing requires that the operations inside firms must be organized and developed properly; companies need to devote specific machinery to restore products and they also must devote floor space for that scope.

These are the main enablers that must be considered for effective implementation of CE strategies.

## 2.2 Business models for Circular economy in manufacturing systems

In this paragraph, the concept of circular economy is applied to manufacturing systems with a focus on a specific business model: Pay-Per-Use.

### 2.2.1 Business model innovation: the concept of servitization

Technologies like the Internet of Things (IoT) are offering new opportunities and posing serious challenges to firms, forcing them to create entirely new business models, migrating from the conventional product-centric approaches to (digitally based) service-oriented ones. [4]

First a definition of what is a business model is provided.

A business model (BM) summarizes the architecture and logic of a business, or the fundamental functions in the strategic life of a firm, it describes the “design architecture of the value creation, delivery, and capture mechanisms it employs”.

There are 4 main elements that compose a BM:

- Value creation, the position and role in the value system.
- Value delivery, the sales model, channels, and customer relations.
- Value proposition, the nature and features of product and services.
- Value capture, the revenue model and cost’s structure.

The improvement and innovation of a BM is called Business Model Innovation (BMI) that may occur whenever the company modifies or improves at least one of the value dimensions.
It is a process through which firms accomplish deliberate changes in the activities and functions within their BMs and explores new architectural designs.

The literature seems to agree on the fact that IoT technology related to data analysis may have disruptive effects on BMs: it may affect firms' internal and external processes and interdependencies, involving reconfiguration of internal capabilities, value and pricing models, revenues and costs structures, and power and collaboration in the value system.

In fact, data gathering, and analysis allows firms to imagine several IoT-enabled servitized value propositions that are at the base of business models redefinitions.

The concept of "servitization" is widely recognised as the process of creating value by adding services to products and developing service-based business models in manufacturing industries.

Digital servitization is the concept of servitization provided by IoT technologies, this phenomenon may be the trigger of a transition from ownership-based business models to non-ownership-based ones, boosting advanced revenue models like pay-per-use, subscription or sharing, introducing a completely new value-capture mechanism.

This implies that the product ceases to be the only reason for the business relation and becomes instead just an element of that relation, because the product is no more sold to the customer, but the product is a service that is provided to the customer.

This can be feasible with the implementation of technologies that can permit to monitor machine usage, machine state, machine reliability and to gather data from usage that can be used for further improvement of services.

Moreover, a literature review by Suppatvech et al. [5] identifies different benefits related to IoT-enabled servitized business models.

Accord to the study, advanced service-oriented business models based on IoT technologies allow firms to:

- Reduce operating costs.
- Generate additional revenue.
- Maintain a long-term business relationship with customers.
- Increase resource utilization.
- Assess the risks of current product or service provision.

Another study [6] has also inspected the factors that affect firm performance looking at changes in business models and investments in intangibles.

They have compared firms that continued to be managed through an existing business model with matched firms that changed their business model over the period. They found that a modification of the business model has a positive effect on the ability of the firm to perform well. There was also a positive complementary effect on performance of business model change and intangibles. The study found that business model innovation is core to firm performance and that intangibles are positive moderators.

In addition to that, a study [7] has shown that servitization is a change in business practices performed by actors in the organization and its ecosystem. Given the complexity that it introduces, they have found that is not enough for single individuals to change their practices of service development or sales and delivery. Change must be collective, the organization and its customers must engage in collective practices, and/or align their practices accordingly for an effective shift toward a service-based BM.

## 2.2.2 Pay-per-use

Implementing practices aligned with CE concerns can transform the way companies do business, especially in the manufacturing sector. In fact, companies need to face a variety of challenges and changes that require new ways of thinking and doing business.

The challenges or factors that impact CE implementation can be classified in 4 main groups [8]:

| GROUPS | CHALLENGES |
|---|---|
| Cultural aspects | Difficulties in business definition, change in mindset. |
| Risk | Financial risk, operational risk. |
| Stakeholder relationships | Compatibility with the business models of partners, lack of supply network support. |
| Internal processes | Need for design capabilities, for sourcing and manufacturing capabilites, lack of technical and technological know-how. |

*Table 1: Challenges of the CE*

Therefore, the shift to a CE is associated with the need to implement innovative business models that can cope with these new challenges by implementing a systematic and defined approach inside companies.

The transition from linear to circular business models requires comprehensive knowledge about designing new business strategies. This in turn requires participation in collaborative circular networks and engagement with suppliers, manufacturers, retailers, service suppliers and customers to understand where and how value is created.

Given the complexity of the scenario, a key aspect to succeed in this process is the integration and engagement of multiple organizational functions that require specific capabilities.

All the functions needed are listed in the table [8]:

| FUNCTION | CAPABILITES |
|---|---|
| Marketing | Definition of pricing models according to each segment, development of the needed partnerships, management of customer relationships through lifecycle. |
| R&D | Definition of prototype experimentations, understand product design for reliability and durability, design for modularity. |
| Purchasing | Assess material properties, certification process of raw materials. |
| Manufacturing | Understand modular assembly, development of processes for reverse logistics and remanufacturing. |
| Sales | Definition of sales structure, process and channels. |
| Service | Definition of installation and maintenace services procedures. |
| Financing | Financial management of the system. |
| Legal | Risks to provide a service instead of product. |
| Institutional relations | Partnerships with organizations to reorient consumption practices. |

*Table 2: Capabilities for CE implementation*

Among the many possible business models that can be implemented, one of the most promising and perfectly aligned with the concept of CE is represented by Pay-per-use that will be analysed in this work.

In pay-per-use, customers pay a fee that depends on usage that is measured according to clearly specified consumption, output, or other indicators, which nowadays are controllable through sensors connected to the IoT.
This new business model replaces product purchasing because companies continue to own their products and remain responsible for repair and maintenance.
By implementing this new business model, the company does not sell a product but instead does sell a service because the product remains property of the builder, while the customer buys the service provided by the product itself, like a production capacity or a pumping capacity as examples.

Therefore, the customer does not purchase the product ownership but its usage that
can be measured through various indicators (e.g. operational hours, produced pieces). [9]

This will also lead to the introduction of auxiliary services provided by companies as maintenance or repair of product, in fact product companies are responsible for all service activities that are needed to ensure product usage.

Pay-per-use solves two issues that users are facing: firstly, it addresses the issue of financing (equipment users do not invest upfront but pay later, typically from operating cash flows generated by using the equipment); and secondly, it is a risk transfer mechanism form equipment user to equipment maker. Therefore, this new model can attract new customers like start-up that does not have enough capital to purchase the machine. [10]

3 organizational capabilities are needed for and affective implementation of this new business model [11]:

- Financing pay-per-use services: it is relevant to understand strategic customer needs, to estimate the financial impact of pay-per-use services, to collaborate with banks to design appropriate financing schemes.
- Aligning costs to product usage: costs need to be linked to the actual equipment usage through basic conversion of equipment costs into equipment usage costs. Such conversion starts at the equipment level and continues at the component levels.
- Collaborating with customers: sales and service employees must work closely with customers. They must convert customer insights into strategic customer need because they possess valuable knowledge about how customers use the equipment. Therefore, they can predict certain customer actions and have valuable experience on customer misbehaviour.

Given the complexity of the context, 3 main core competences are required [11]:

- Strategizing pay-per-use services: this means that companies should take advantage of remote and self-service technologies measuring, for example, the actual usage of critical components. Therefore, companies can use all the data gathered to improve products and expand their knowledge to increase efficiency and productivity. Moreover, companies need to integrate suppliers simultaneously into the pay-per-use approach.
- Utilizing technologies: technologies for remote services, remote monitoring, self-diagnosis and design optimization of products.
- De-risking pay-per-use services: Since customers pay for usage, revenues are the result of the usage fee deriving from the actual product usage that replaces individual sales. This represents a risk for manufacturers, because they do not have a defined and constant value of incomes that depend on the level of usage of their products. To reduce this risk, it is possible to introduce a minimum-order clause in the contract, which means that a constant fee must be pay by the customer independently from the usage of the product. On top of this minimum fee, the customer pays dependently on the usage of the product.

The main core competences that will be analysed in this work will be strategizing services and the utilization of technologies in a pay-per-use business model considered for manufacturing companies.

More specifically, the sector that will be investigated will be the assembly industry that can take a great advantage by implementing this business model.

Moreover, the main target will be related to the design and management of assembly machines that need to be adapted and changed specifically for these purposes.

The main change is related to the fact that, in a pay-per-use business model, a machine will be used by the client as a service for a limited period, and after that, the client can decide that he needs a new machine, or he does not want the machine anymore.

This is extremely different respect to the past, because in the past once machines were delivered, they were property of the client.

In the future, the machine, after a period of service to the client, returns to the builder, this means that the manufacturer must reuse the machine for other purposes. This is a strong issue because it introduces a concept that is fundamental: machines must be easily reconfigured.

## 2.3 Reconfigurable manufacturing systems (RMS)

A reconfigurable manufacturing system (RMS) is the latest manufacturing paradigm which promises to meet all modern days' challenges posed by the manufacturing environment. This manufacturing system is designed for speedy change in its structure, as well as in hardware and software to swiftly adjust as per the requirement of production capacity and functionality, this is a key point for the design of machines in the context of CE. [12]

First, a comparison with the other manufacturing system must be performed.

A traditional manufacturing system like dedicated manufacturing system (DMS) can produce similar products but is highly inflexible toward variety.

In contrast, a cellular manufacturing system (CMS) is a group technology-based manufacturing system which is designed around fixed set of part families. CMS has the goal to improve the productivity when many products are to be manufactured in medium to small quantities. In CMS, changing the product variety, variable demands and/or changes in operation sequences may disturb the composition of part families for which the cells are originally designed as the operations must be completed inside the cells. Therefore, the task to reconfigure structurally inflexible CMS is highly impractical, costly and time consuming.

FMS can produce high variety products but with low production capacity. Besides, the operating and installation costs of FMS are high and therefore, FMS has very limited acceptability among the manufacturers. [12]

Therefore, RMS can be designed to be a DMS or an FMS or in between and can be changed as and when required. RMS is proposed to combine the throughput of a DMS and flexibility of an FMS to react to the market changes economically and effectively.

All these characteristics make the RMS the perfect system that must be implemented for a successful pay-per-use business model.

A RMS is extremely suitable specially for assembly systems that are the focus of this work.
A reconfigurable assembly system must perform a sequential series of tasks that can be obtained by the successive introduction of different activities, by contrast, considering a reconfigurable manufacturing system will lead to a very complex interaction of different parameters that produces a very complex function.

The logic of a RMS is shown in figure:

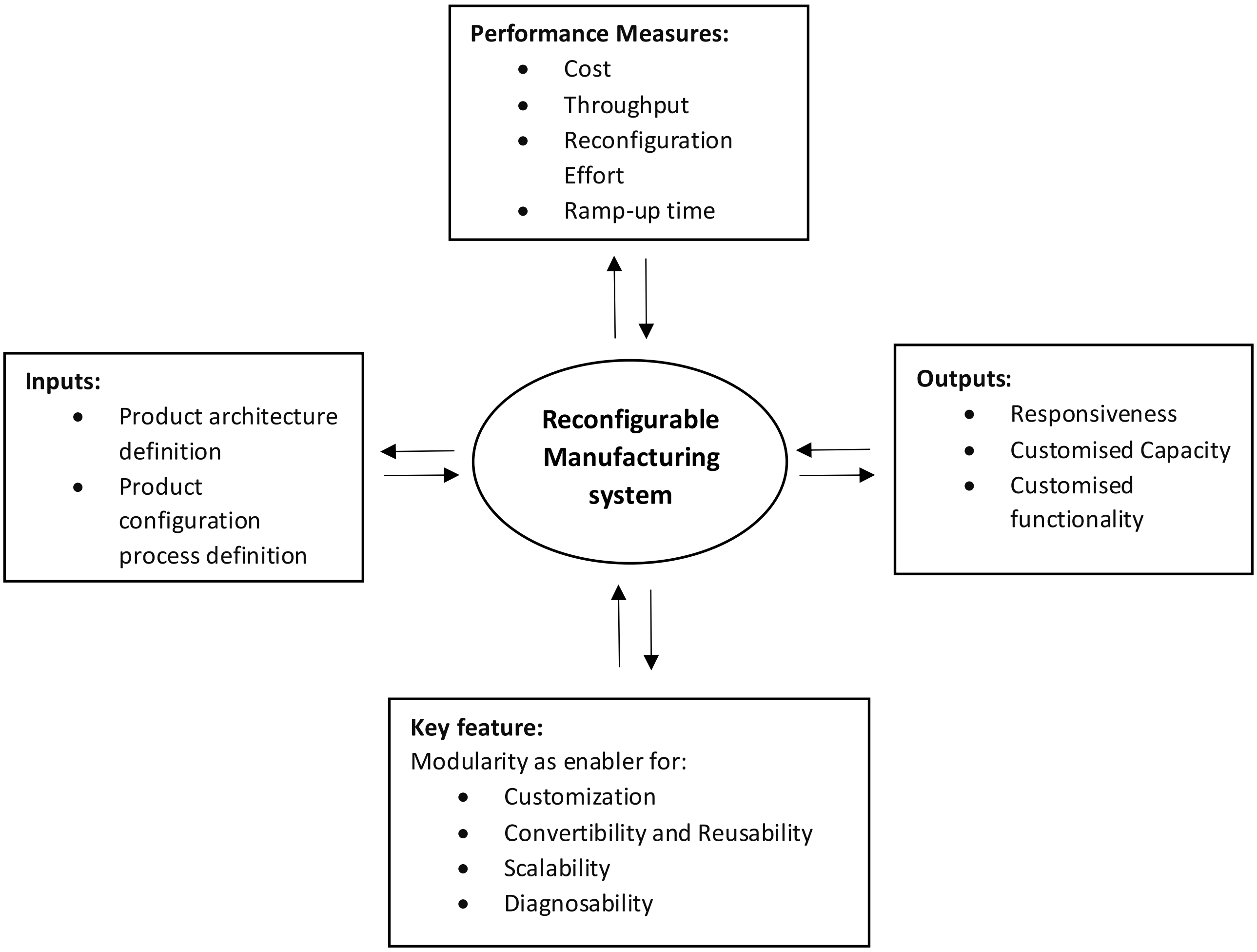


*Figure 3: Reconfigurable manufacturing system*

The inputs related to a RMS are the design architecture of the product and, directly related to that, the configuration process: both these aspects are completely different respect to traditional manufacturing system.

Performance measures (e.g. throughput, availability, and ramp-up time) will obviously influence the final configuration of the RMS and they can represent constraints.

As output, responsiveness is a key quality because by reconfiguring a pre-existing machine the time to respond to demand can be reduced, therefore this is an important advantage that can be exploited against competitors that have to build the product from scratch. Another relevant factor is the possibility to obtain customised capability and functionality, this means that it is possible to reconfigure the machine to specific needs of the client while assuring high performances and high quality.

### 2.3.1 Automated multi-stage assembly systems

The reconfigurable manufacturing systems that will be considered in this work are automated multi-stage assembly systems.

Assembly systems are considered extremely suitable for a reconfigurable approach, because the operations that must be performed are sequential and therefore the system can be composed by different units that are independent among them. This implies that the process of reconfiguration will be much easier respect to manufacturing systems in which different operations are extremely interconnected resulting in much more difficult modular approach.

Automated means that the assembly systems considered are composed by stations in which the operations are performed by automatic machines and manual operations are not present. This implies that the products that can be assembled by these systems have limited dimensions and the production volume that can be reached is high (e.g. 1 piece/second).

These assembly lines can be used to assemble products of different industries:

- Furniture industry (e.g. drawers slides).
- Automotive industry components (e.g. brake disks).
- Medical/Cosmetic industry.
- Electromechanical industry.

## 2.3.2 Modularity

As shown in figure 3, there is a main key feature that will be at the basis of a RMS:

- Modularity: The compartmentalization of operational functions into units that can be manipulated between alternate production schemes for optimal arrangement.

Modularity can be seen as an enabler of other features:

- Customization: System or machine flexibility limited to a single product family, thus thereby obtaining customized flexibility.
- Convertibility and reusability: the capacity to quickly transform the functionality of existing systems and machines to suit new production requirements.
- Scalability: The capacity to quickly modify production capacity by adding or subtracting manufacturing resources (e.g. machines) and/or changing components of the system.
- Diagnosability: The capability to judge the present state of a system to detect and diagnose the important causes of output product defects, and promptly rectify operational defects.

A survey on these features has been conducted on 70 research papers to understand which one is considered the most relevant for the implementation of a RMS.

The results are shown in the following figure:

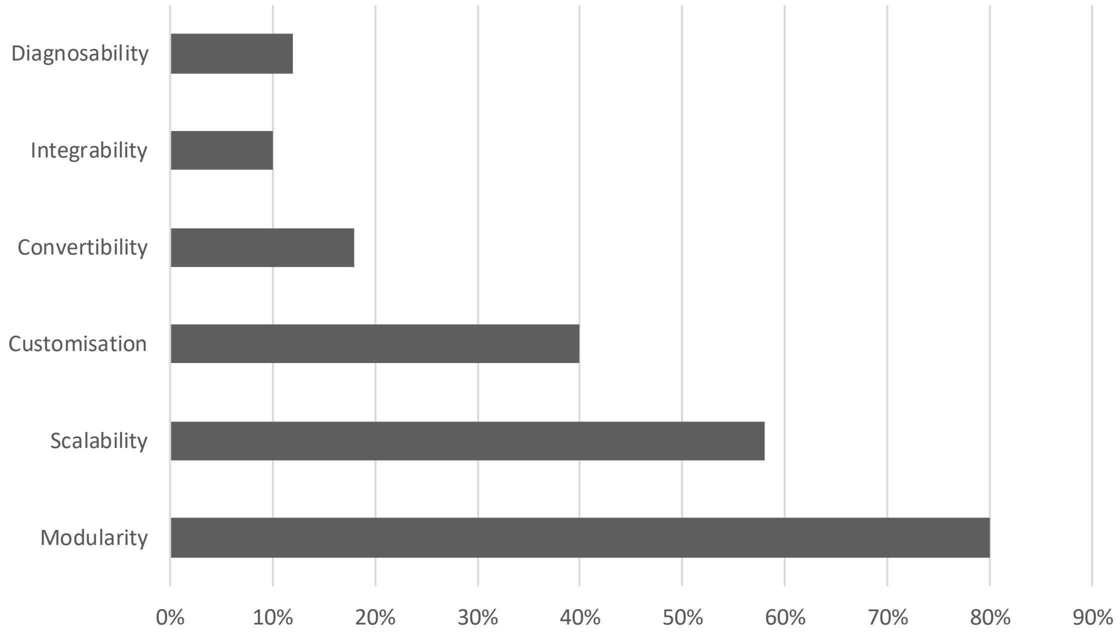


*Figure 4: Survey on features of RMS*

As can be seen, modularity has been considered by 80% of the authors the most relevant and thus the most critical aspect that must be regarded to obtain an effective RMS, followed by scalability (58%). [12]

There are several definitions of modularity, it is frequently defined as "Building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole". [13]

Modularity is a design strategy that avoids creating strong interdependencies among specific components (modules) within the product. A module can be seen as a group of components that can be removed from the product non-destructively as a unit.

Therefore, a modular product fulfils various functions through the combination of distinct building blocks called modules that are commonly described as groups of functionally or structurally independent components.

Product modularity (PM) is the use of standardized and interchangeable components or unit that enable the configuration of a wide variety of end products.

There are different characteristics that can be associated to PM:

- Separateness: it refers to the degree to which a product can be disassembled and recombined into new product configurations without loss of functionality.
- Specificity: it refers to the degree to which a product component has a clear, unique and definite product function with its interfaces in the product system.
- Transferability: it refers to the degree to which product components in a product system can be handled over and reused by another system.
- Flexibility: a modular product is flexible because different product variations ca be achieved by substituting different modular components into the product architecture and provides

the potential for many product variations with distinctive functionalities, features or performance levels. A modular architecture also enables companies to upgrade their products throughout their life cycles.

Several further concepts have been associated with modularity. They include architectures and platforms, interchangeability or loose coupling of components, standardization of interfaces, and one-to-one matching of module and functions.

All the above-mentioned concepts are extremely useful for an effective RMS design and thus an effective implementation of a pay-per-use business model. Thus, it can be easily understood the importance of modularity in a context of circular economy.

### 2.3.3 Advantages of modular products

The first big advantage related to modularity involves the creation of product variants based on the configuration of a defined set of modules.
Trough modularity, the number of parts to be manufactured may be significantly reduced while achieving sufficient variety by combination of different modules.
The figure shows various combinations of modules resulting in formation of variants of modular product. [14]
In this case as an example, by considering 3 type-A modules and 2 type-B modules it is possible to obtain 6 variants of the final product.

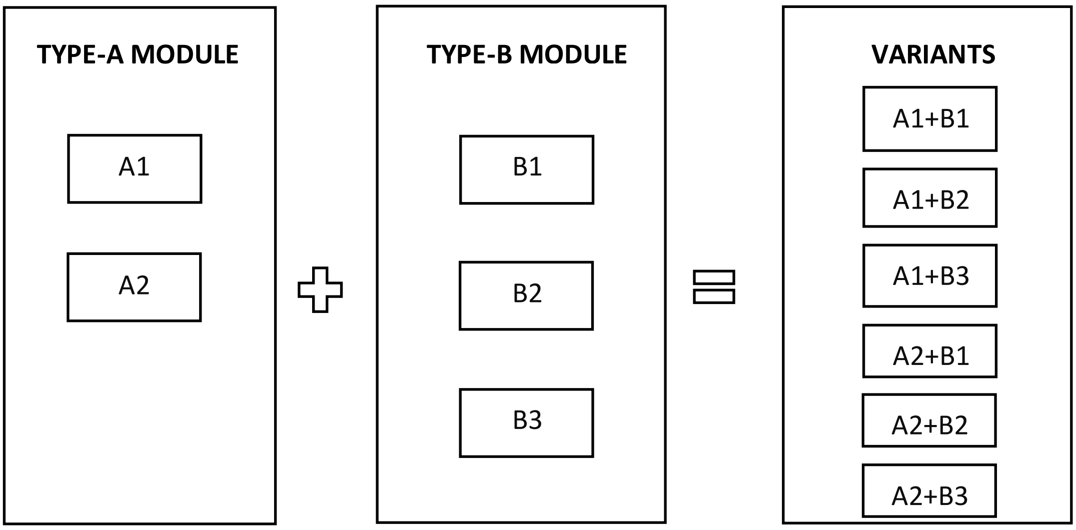


*Figure 5: Composition of a modular product*

Therefore, quick response to different circumstances can be achieved by choosing the best variant. Different product variants can be developed by choosing different combinations of the module instances.

This concept can be an extremely useful results in manufacturing industry for producing customized machines by combining existing subsystems.

Another advantage is related to the fact that a product can be easily disassembled so that single modules maintain their value. The higher the degree of modularity in the product, the higher the reduction in the loss of value. To reduce environmental impact of industrial products, it is mandatory to rationalize product design and to achieve a closed loop product life cycle by reusing and recycling of the parts. Obviously, it is difficult to reuse the parts based on conventional product structure, and appropriate product modularization is necessary to efficiently manage a closed-loop product life cycle.

This is a clear explanation of the importance of modularity in a CE based business model, like pay-per-use, especially in the manufacturing industry in which the products are extremely complex with enormous number of components. Therefore, it is even more relevant to re-use this machinery to obtain environmental and economic benefits.

In fact, a manufacturer can recollect the machine, can decompose it to obtain individual modules and can rebuild another machine with limited effort for another purpose just by combining modules in different orders.

Another advantage related to design is the reuse of information, in fact by producing a standardized module the design is always the same.

Modularity also allows further reduction of service cost by grouping components so that the less reliable components are easily accessible, this is relevant to minimize the lack of time for service or repair.

Summarizing, the advantages of modular design are:

- Device reconfigurability
- Speedy introduction of new devices
- Maintainability and serviceability of devices
- Design information reuse.

## 2.3.4 Machine architecture design

The core aspect for an effective implementation of Pay-per-use BM is related to the architecture of the product that will be completely different respect to the conventional product design.

The type of product that will be investigated in this work is a manufacturing system, more specifically an assembly system.

The key concept to obtain a reconfigurable manufacturing system is related to the development of a completely new machine architecture design that can be obtained through modularity and standardization.

## 2.3.5 Drivers of modularization

First, a literature review of the most cited drivers of modularization is provided to clearly understand which are the key advantages of a modular product.
The two most cited and strongly interlinked benefits of product modularity are the ability to reach high product variety while keeping a relatively low and manageable internal product variety for the product development process. [15]

Additional drivers are:

- Breaking down the product complexity is cited to reduce the development time by allowing parallel development and, thus, to lead to a shorter time-to-market and reduced development costs.
- Modularity is identified as an important aspect for product maintenance – notably because it allows separated diagnoses of product components and isolation of wear parts – which is, in turn, identified as an aspect of environment-friendly product design.
- The possibility to upgrade, adapt or modify the product for extending the service life of a product or parts and, therefore, reduce the environmental load of products is another cited potential benefit of modularity.
- Modularity is expected to lead to a reduction in production costs due to postponement and delayed differentiation.
- Decreasing the interface complexity between product parts allows the distribution of design tasks, reduces the required intensity of communication between teams and, therefore, allows faster design changes.
- Product modularity affects the ability to disassemble the product at its end-of-life; hence, the ability to sort parts according to their most appropriate post-life treatment (repair, reuse, remanufacturing, recycle and disposal) and the environmental load of products.

The table below summarises the number of citations of each element found in literature:

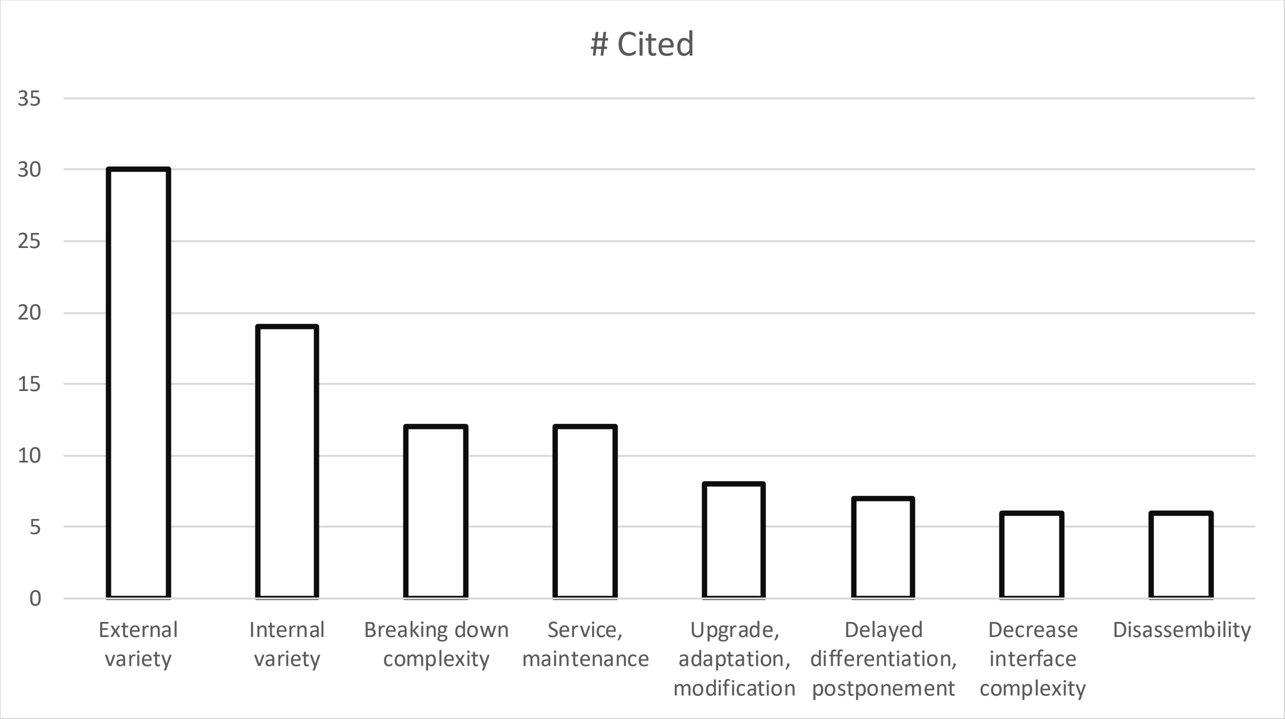


*Table 3: Key modularity drivers*

Considering specifically an assembly system, it is extremely important to define 4 levels of modularity:

- Mechanical modularity.
- Software modularity.
- Electronic modularity.
- Pneumatic modularity.

The combination of these 4 levels of modularity is a key concept to introduce a PPU business model because by combining different modules related to different functions it is possible to obtain different lines for different purposes.

This is necessary because the life cycle of the products will be much shorter compared to conventional business models since a customer requires a product for limited period. Therefore, the speed of introduction and the reconfigurability of the product must be achieved through modularity.

Mechanical modularity is obviously the starting point to develop a modular assembly system, this is referred to the fact that mechanical components need to be designed to perform a defined and specific assembly function.

To obtain a robust architecture, also the software must be modular. In fact, each module will have its dedicated software that will not require any subsequent coding activity and this it will increase the speed for the introduction of new lines or reconfiguration of old ones.

Moreover, a third aspect must be considered: the modularity of the electrical components linked to the module. This assure that each module has its dedicated electric components, following the same reasoning of the software.

For this aspect, the fieldbus and the powerline must be properly designed to be modular.

The last aspect that must be considered to obtain a product that is completely modular is related to pneumatic components, in fact they must be developed following the same reasoning of the other 3 categories.

By combining all these aspects, the module is a completely independent entity that can be used to compose an assembly line.

### 2.3.6 Standardization

An additional key aspect that must be developed is related to the concept of standardization that is an essential enabler to increase the speed of configuration and reconfiguration.

A modular product is a special model to create flexible product architecture by means of standard interfaces, this explains the importance of standard interface to modularization, and the compatibility of interface and architecture. [16]
A firm must consider both internal and external interfaces at the same time when evaluating interface strategy.
By setting standard interfaces, product can achieve replaceable, upgradeable, and functionally variable abilities by means of variant functional subsystems which allow it to construct different products. [17]

The first concept that must be taken into consideration is related to the interfaces inside the modules.

- The most critical components (like pneumatic or electric actuators) require standard mounting interfaces that will lead to fast repair and substitution.
- Engines (e.g. brushless motors) are required to move components or subassemblies; therefore, they are needed for many different modules. This implies that, during reconfigurations or revamping of the machine, they could be substituted.
  Thus, universal mechanical interfaces are needed to reduce as much as possible time for substitution.

Also, the external interfaces need to be considered, in fact in an assembly system they are necessary to connect the modules to the assembly line.

Therefore, the external interfaces of the modules need to be standardized to achieve fast and efficient link between the modules and the basement of the assembly line.

As reported in [23], the internal and external interface can enhance the product variation, and, as the product matures, the level of effectiveness of the standardization will increase.

# Chapter 3 – Formalization and analysis of Pay-Per-Use business model in automated multi-stage assembly systems

In this paragraph all the key aspects that must be implemented for effective development of a PPU business model are listed and explained, with a focus on product architecture design, machine configuration and reconfiguration.

The functions that must be considered to properly implement a PPU business model are:

- Financial.
- Machine architecture design.
- Procedure to design specific configuration.
- Lifecycle analysis of modules.
- Monitoring and maintenance.
- Disassembly and remanufacturing.
- EOL treatment.
- Module management and logistics.

An **IDEF** scheme can be used to understand which will be the flow of information and materials between the different organizational functions once a PPU business model is applied.

The **IDEF**, that is now described, is reported in **Annex 1**.

**NODE A0** – PPU logical flow

The first scheme explains the general logical flow that a PPU implementation will produce in a manufacturing company.
Starting from a request of the client, the flow of information inside the company and with the client is reported. This process ends with the definition of the manufacturing operations once the proposed assembly system is accepted by the client.

**NODE B0** – Assembly of a new product

This explains the need of the client to assemble a new product, this will lead to the request of a new assembly line that will be proposed to the sales department of the manufacturing company.

**NODE A1** – PPU Physical flow

This scheme explains the physical flow that a PPU implementation will produce in a manufacturing company. This flow starts with the delivery of ordered materials and with the delivery of required modules from the warehouse.

The main difference respect to a conventional BM consists of the Recollection and Remanufacturing process (NODE H1) that is the end of the physical flow. Another difference that must be considered is related to the fact that the assembly line will be constantly monitored by the engineering department to define possible maintenance operations and lifecycle analysis of data that will be then used to improve quality of the modules.

**NODE H1** – Recollection and Remanufacturing process

This node explains the process that must be performed once an assembly system is recollected after a lifecycle is completed. This includes the analysis of the modules conditions that defines if a module can be remanufactured to restore its value or if the module must be disposed with an EOL treatment.

**NODE D0** – Configuration of the solution

Once a new request of product is received, the engineering department must identify the optimal solution for the client. This implies a new configuration process respect to a conventional BM because the product will be composed by the modules. This process is based on the product architecture definition in which the key elements (functions library and modules library) are defined. The output will be the formalization of the solution that will be used by manufacturing ang also by financial department.

**NODE N1** – Product architecture definition

This explains the process that must be performed by the engineering department to define the new architecture of the assembly systems. This process will be in continuous development because new needs from customers and newly identified solutions will define upgrades to the modules library and functions library.

**NODE E0** – Financial evaluation of the solution

Once the optimal configuration is identified during the configuration of the solution, the financial department must evaluate the financial feasibility of the solution and must define the fees for the client.

**NODE F0** – Definition of manufacturing operations

This scheme explains the manufacturing process that must be performed once the proposed solution is accepted by the client that will lead to the final product execution.

## 3.1 Financial

The introduction of a new business model like PPU completely changes the revenue model of the company and therefore a financial analysis must be considered and performed.

The detailed study of the revenue model is not the scope of the dissertation but some information are provided given the importance of this topic to effectively implement a PPU business model.

Considering a traditional business model, the manufacturer receives the payment that covers the costs when the machine is delivered to the client; this mechanism cannot be applied in a PPU business model because the fixed and initial cash flow will not be present anymore.

The revenue model will be based on the monetary return of the lease of the production capacity, and it becomes profitable only if the machine will be re-used for many life cycles.

Therefore, the cash flow will be directly related only to the fee that the customer pays to use the production capacity of the machine, this can represent a risk for the manufacturer because the customer can decide to use the machine with very low production rate that will lead to limited cashflow and loss of money for the producer.

To solve this financial issue a strategy to reduce risk can be implemented.

The customer pays a fixed fee every working day plus a remuneration for each piece produced by the assembly line. A minimum number of pieces to be produced in the system is stipulated a priori in the contract, and in case it is not respected, the supplier can break the contract, as it becomes economically unfeasible to recover the cost of the plant in the long run.

Given that the modules that compose the RMS are reused for several lifecycles, this scheme may provide higher revenues per assembly system and may attract new customers; however, the cash flow is changed, and the highest profits are made toward the end of the machine lifetime.

The negative cash flow related to the investment at the beginning creates the need to finance the first years, because manufacturers usually do not have enough liquidity to afford that type of investment.

To cover the costs related to the fabrication of the system, both related to the acquisition of components from suppliers, salary of the employees and other operational costs that must be disbursed upfront, other financial institution like banks or investment banks must be considered. This implies a strict collaboration with these stakeholders that becomes the financial owner of the system.

Another viable path to cover part of the upfront costs is the institution of partnerships with suppliers, moving upstream part of the risks related to missing revenues.

Another additional stream of revenues to be considered is the one related to accessory services, such as maintenance, that is strategic for the manufacturer as it increases the lifecycle of the modules.

## 3.2 Procedure to design precise machine configuration

In this paragraph, the methodology that is necessary to implement to properly design and configure a modular assembly system is explained.

A modular reconfigurable machine is designed based on building blocks, called modules. In this chapter the steps that must be carried out to design a modular assembly machine are listed and explained.

The first point is related to the input of the system that is a set of parts to be assembled, called part family, each part sharing some features but differing in others. The output is the final design of a reconfigurable machine that can use a minimal set of modules to assemble all the parts within the family. [18]

The objective of the machine configuration is to develop a link between the input which is a part family and the output which is the final design of the manufacturing system.
Therefore, a defined process must be developed because the traditional configuration of a manufacturing line cannot be applied due to the introduction of the modules that will compose the final product.

A summary of the process that will be analysed in the following chapters is provided:

1. When a given family of parts is given as input into the design system, a set of assembly features will be extracted and linked to machine modules.
2. Then, a set of machine modules will be selected and evaluated to form a minimum set of modules.
3. Finally, a final design will be determined based on several performance indices.

All the elements that are required to properly implement the configuration procedure can be summarized in the following table:

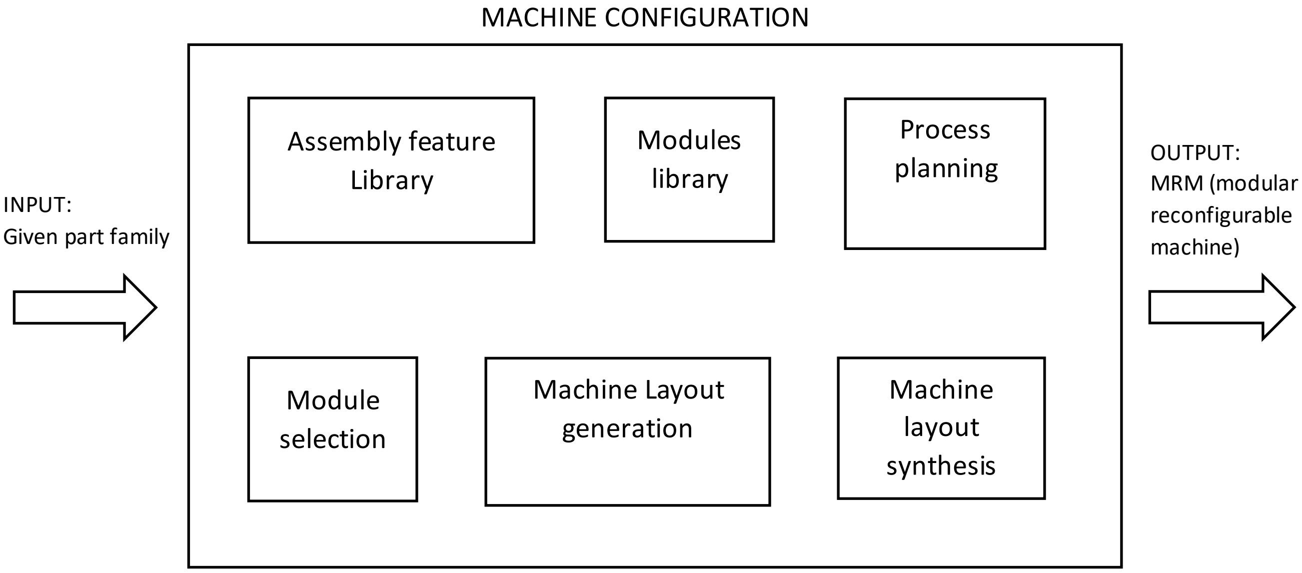


*Figure 6: Elements required for modular reconfigurable machine creation*

Therefore, the machine configuration can be seen as a transfer function between the input, that is the part family that must be assembled, and the desired output that is the modular machine that we want to configure, as shown in the following figure:

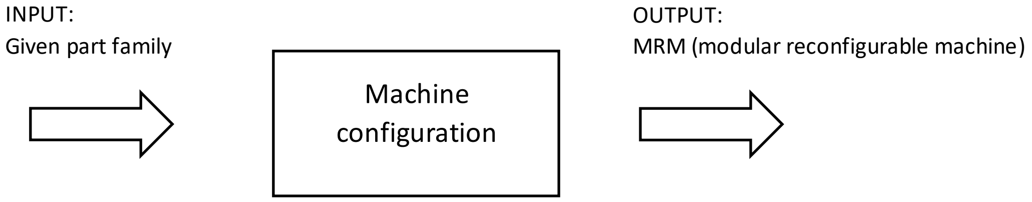


*Figure 7: Input - output link*

In the following paragraphs all the different elements that compose the machine configuration and the methodology implemented will be explained.

### 3.2.1 Assembly features library

This library will include all the possible features that can be used for assembly purposes, this defines all the functional groups that will constitute the assembly machines.

This is the base of the whole process because it defines all the functions that will be needed to assemble the final products and therefore it is important to understand the variety of modules that will be required because each function will be linked 1 to 1 to a module.

To obtain the library a top-down approach is implemented, this implies to start from a production or manufacturing process that will be decomposed in classes, processes and finally operations.

The approach is shown in the figure [19]:

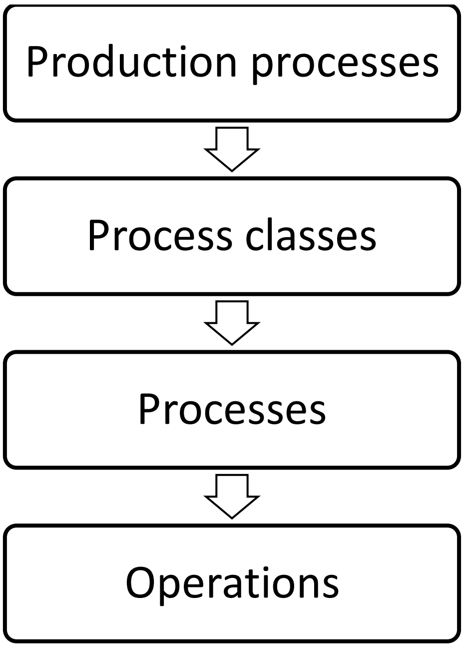


*Figure 8: Assembly features library creation process*

Production processes: all actions involved in the creation of products, it contains fabrication and assembly processes. In the following, only assembly processes are considered because it is the focus of this work.

Assembly process class: a group of assembly processes for the performing of similar assembly functions. They define the functions of the assembly process.

Assembly process: a distinct process out of a class of processes.

Assembly operations: a single action changing only one aspect of the state of the object acted upon.

An example of a screwing process is now reported to properly understand how the top-down approach works.
The process can be decomposed as follows:

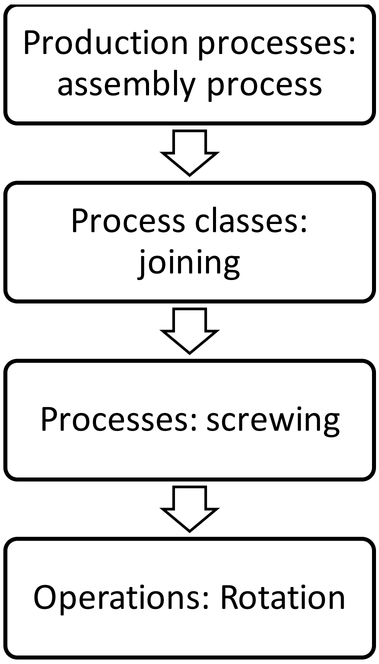


*Figure 9: Assembly features library example*

Therefore, all the possible functions needed can be classified to obtain a function library that contains all the process classes that are required (in this work only the assembly process is considered).

The main classes considered are:

- Transportation, this is related to the definition of the transportation system chosen for the assembly line.
- Pick and place, this defines how a component will be picked from the feeding system and placed in the correct position on the line.
- Feeding, this defines how the components will be fed to the line.
- Joining, this defines all the possible processes that are considered to join components.
- Plastic deformation, this is related to bending of components for assembly purposes.
- Visual inspection, this defines how inspection related to presence of components, surface quality and others are performed.
- Functional inspection, this is related to the need of testing a defined function of the part.
- Contact inspection, this is related to strength capabilities of the product to be assembled and it can be divided in destructive and non-destructive.

In each class possible alternatives that belongs to the same functional class are listed; this implies that not only the needed function has to be defined but also the precise process must be chosen.

The table represents the assembly features library considered in this work that is referred to assembly process of small components with high production volume:

| ASSEMBLY PROCESSES |
|---|
| Classes: |
| TRANSPORTATION |
| Linear conveyor |
| Rotary table |
| PICK and PLACE |
| 2D (cam) |
| 2D (arm) |
| 3D (robot) |
| JOINING |
| Screwing |
| Riveting |
| Welding |
| Soldering |
| Shrinking |
| Gluing |
| Clinching |
| PLASTIC DEFORMATION |
| Bending |
| MATERIAL REMOVAL |
| Tapping |
| FEEDING |
| Vibratory feeding system |
| Manual feeding |

*Table 4: Assembly features library*

| INSPECTION: |
|---|
| Presence |
| Inductive sensor |
| Capacitive sensor |
| Optic sensor |
| Magnetic sensors |
| Vision system |
| Position/distance |
| Optic sensor |
| Ultrasound sensor |
| Vision system |
| Shape |
| Vision system |
| Surface finishing |
| Vision system |
| Contact (Non destructive) |
| Strength |
| Contact (Destructive) |
| Tear strength |
| Functional |
| Linear actuation |
| Torque |

*Table 5: Quality check features*

Once all the functional group have been defined, the modules library can be developed.

### 3.2.2 Modules library

This library is a module database that contains all the elements that will compose assembly machines.

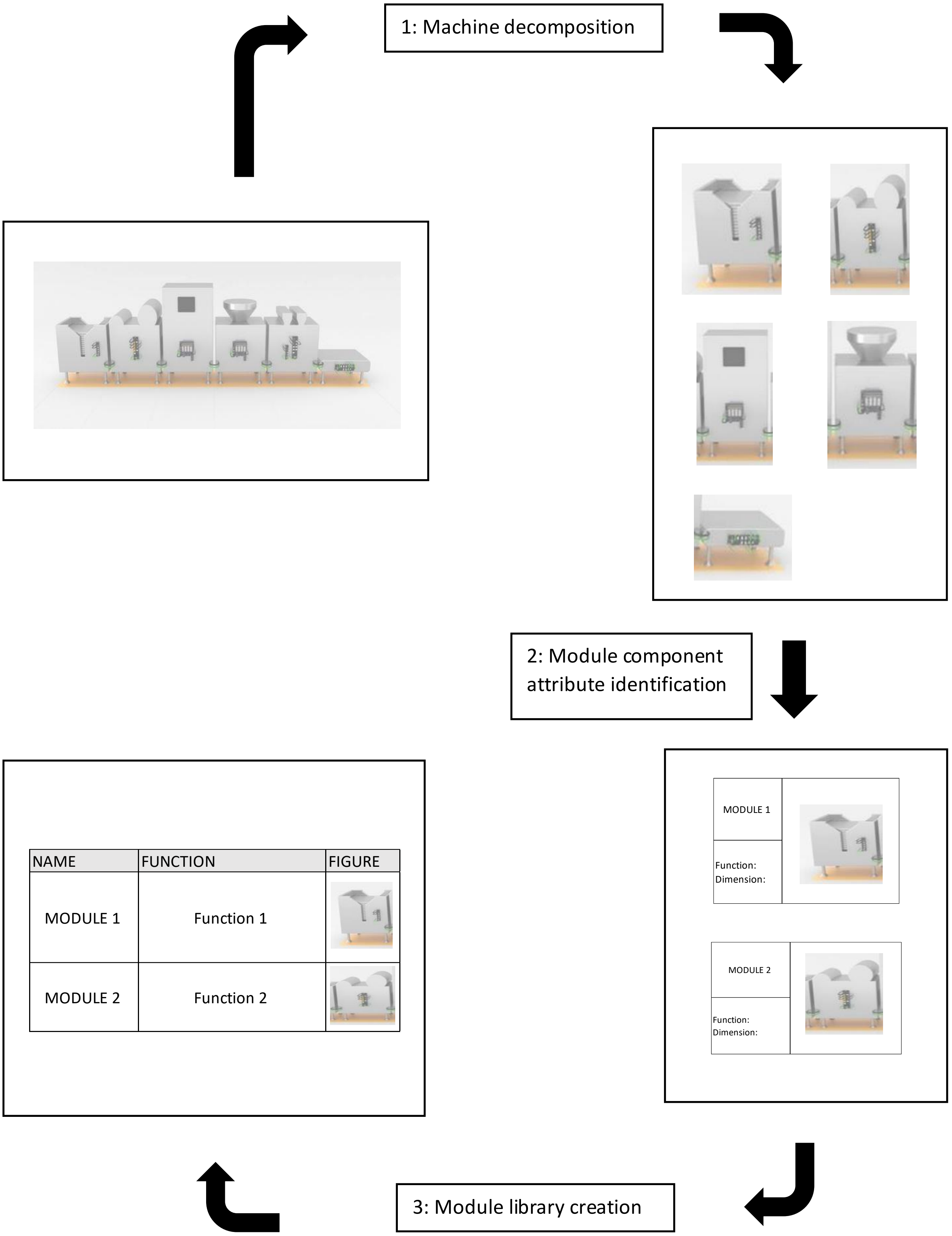
Researchers [20] have identified that a methodology that can be implemented to create a RMS consist of the fabrication of a library of precompiled mechanical modules from which machines may be assembled.

It can be obtained by decomposing a machine in its components, the modules, that can perform defined tasks. Each module can be mapped to obtain a precise classification.

Starting from the function's library, it is possible to assign a defined function to each module.
The process can be synthetizing as follows [18]:

1. The first step is related to the decomposition of a machine in its functional groups that will be the modules of the library.
2. Once the machine has been decomposed, all the modules need to be identified and classified to link a function to each of them.
   To perform a complete characterization, additional information must be identified: length, width, production rate in isolation, MTTF, MTTR, and cost.
   For a newly developed module it will not be possible to have all this information since the beginning, but they can be obtained through implementation of a monitoring system.
   The mentioned characteristics of each module will be needed to perform the configuration process and the subsequent performance evaluation.
3. The last step is related to the creation of the database that contains all the modules that will be used as a library to configure the assembly machine.

The process is shown in the figure:



| NAME | FUNCTION | FIGURE |
|---|---|---|
| MODULE 1 | Function 1 | |
| MODULE 2 | Function 2 | |

*Figure 10: Modules library creation*

A table with the list of the characteristics that will be required to implement the configuration process is now provided:

| Identification | Function | Lenght (m) | Width(m) | Production rate in isolation (pieces/s) | MTTR (s) | MTTF (s) | Cost (euro) |
|---|---|---|---|---|---|---|---|
| Module 1 | | | | | | | |
| Module 2 | | | | | | | |

*Table 6: Modules Database characteristics*

### 3.2.3 Line configuration methodology

Once the 2 libraries are defined it is possible to define the process that will be implemented for the generation of the line configuration.
The process is iterative because not only one configuration is possible given that there are different possible alternatives due to technical factors related to the process planning or due to economical or flexibility factors.

The line configuration process is reported:

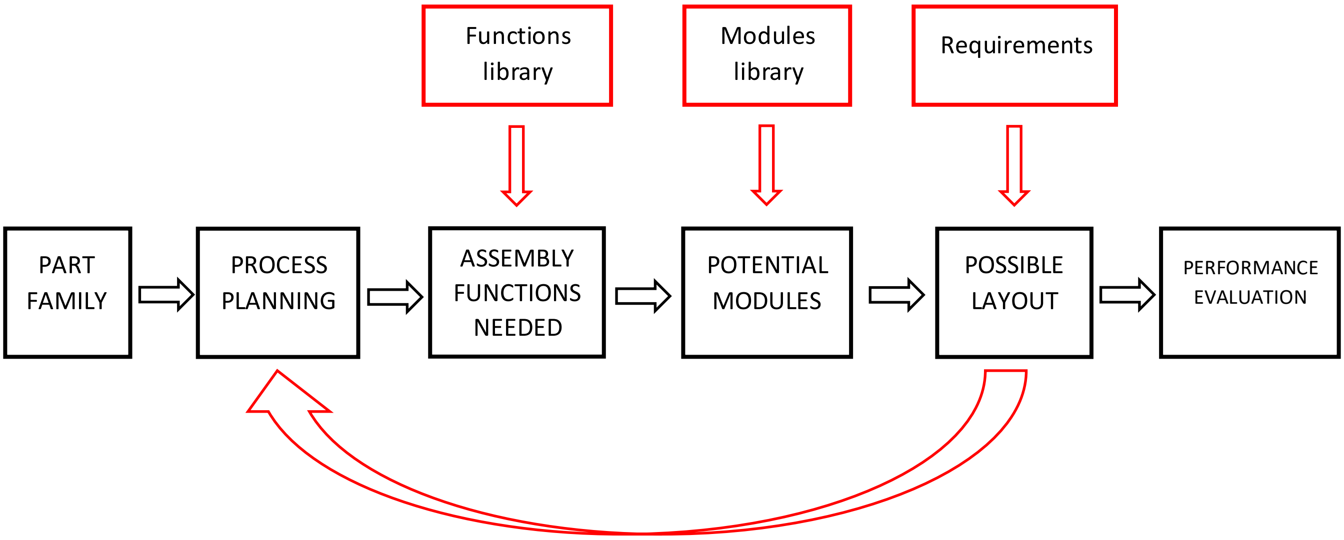


*Figure 11: Line configuration methodology*

In the following paragraphs all the steps will be presented and explained.

## 3.2.4 Process planning

The Assembly Planning aims to identify and evaluate the different ways of constructing a mechanical object from its components: “Given a geometrical and technological description of a product, find an assembly sequence that satisfies the precedence relations between operations and meets certain optimization criteria” [21].

The sequence for the assembly of a set of parts in an assembled product is the most basic requirement for the assembly planning of that product.
It plays a key role in determining the important characteristics of the assembly tasks and of the finished product assembly.
The choice of an assembly sequence affects several other functions and features such as: [22]

- The difficulty of assembly steps.
- The need for fixturing.
- The changing of tools during assembly.
- The potential for part damage during assembly.
- The ability to do in-progress testing.
- The efficiency of the assembled process.
- Unit cost of assembly.

The process planning contains 2 main steps:

1) Assembly modelling
2) Generation of all feasible assembly sequences.

Assembly modelling is related to the decomposition of the product in its subassemblies and components to understand the product structure.

Generation of all feasible assembly sequences is related to modelling of all the sequences of steps that must be performed to assembly the final product, this step can lead to creation of different possible assembly alternatives.

## 3.2.5 Assembly modelling

The data needed for assembly modelling can be obtained by the CAD and the BOM of the part that must be assembled.

First, step is hierarchical object representation that decomposes the final product in subassemblies, and subassemblies into components.

An example of a hierarchical object representation is reported:

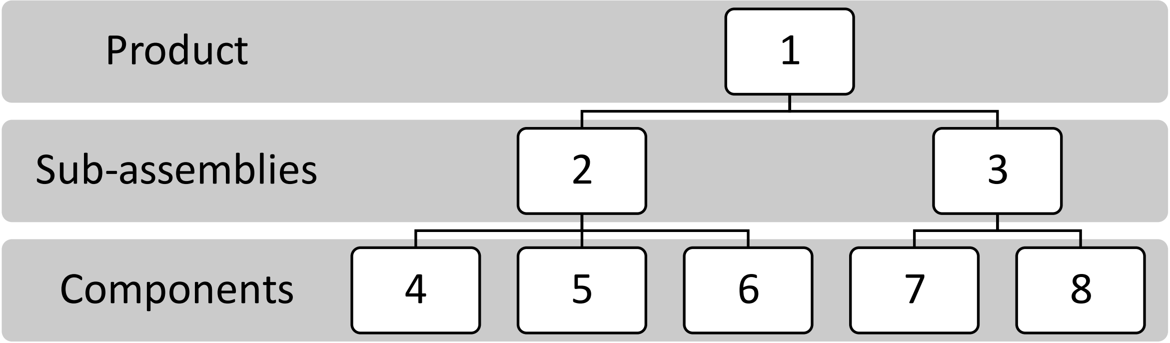


*Figure 12: Assembly modelling for process planning*

This step is important to understand if a product is composed by different subassemblies that can therefore be assembled on parallel lines to maximize the production rate.
For the subassemblies we understand that we need multiple assembly lines that need to be linked at the end of each process for the final assembly process.
From this step it is possible to understand the number of lines that must be configured.
In the example shown in the figure, it will be required to design 2 parallel lines for sub-assembly 2 and 3 plus a final assembly line for the final assembly of the product 1:

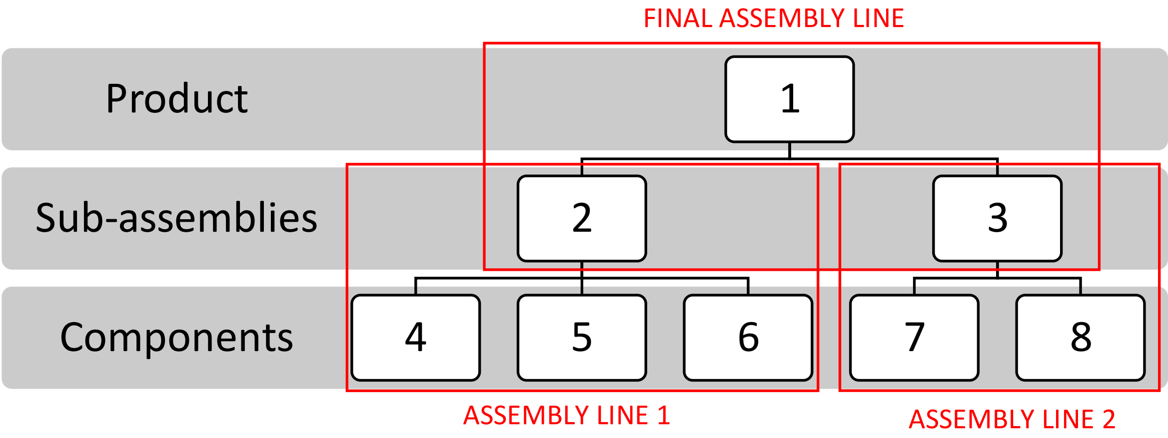


*Figure 13: Assembly modelling, number of lines required*

## 3.2.6 Generation of assembly sequences

For the assembly of the components related to each subassembly it is possible to define the assembly constraints, which consist of precedence constraints among the components and then representing them explicitly.

As an example:

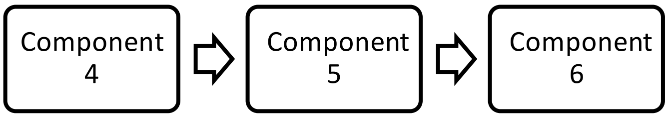


*Figure 14: Assembly sequence example 1*

This is important to understand which is the series of step that must be considered for the generation of the assembly process.

Obviously, it is possible that there are different alternatives due to lack of direct precedence, as an example:

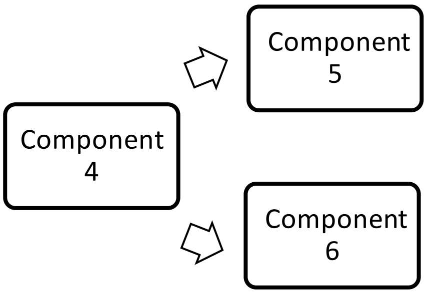


*Figure 15: Assembly sequence example 2*

In this case, two feasible sequences can be obtained; it is possible to assemble first component 5 or it is possible to assemble first component 6.

This explains why the concept of line configuration must be considered as an iterative process since there are multiple possible alternatives that can be considered and evaluated.

To define all the possible assembly sequences a tool that is controlled via web-based Graphical user Interface can be adopted: the Assembly sequence Generation (ASG).

This IT tool is implemented within a commercial software package, utilizing macros written in the VBA macro language. It is based on collision detection model that performs a disassembly process on the product assembly CAD file, it generates the assembly sequence by essentially revising the disassembly process [23].

Once, all the sequences have been defined it is possible to define and to represent graphically the series of operations that must be performed. This will be the final output of the process planning, that will be used for the next steps of the machine configuration.

In this graph, that is a logical sequence of all the operations that must be performed it is necessary to include how to feed the components, how to pick and place them, which are the links between different components, and if a quality check task is needed.

An example of the graphical representation is shown in the figure below:

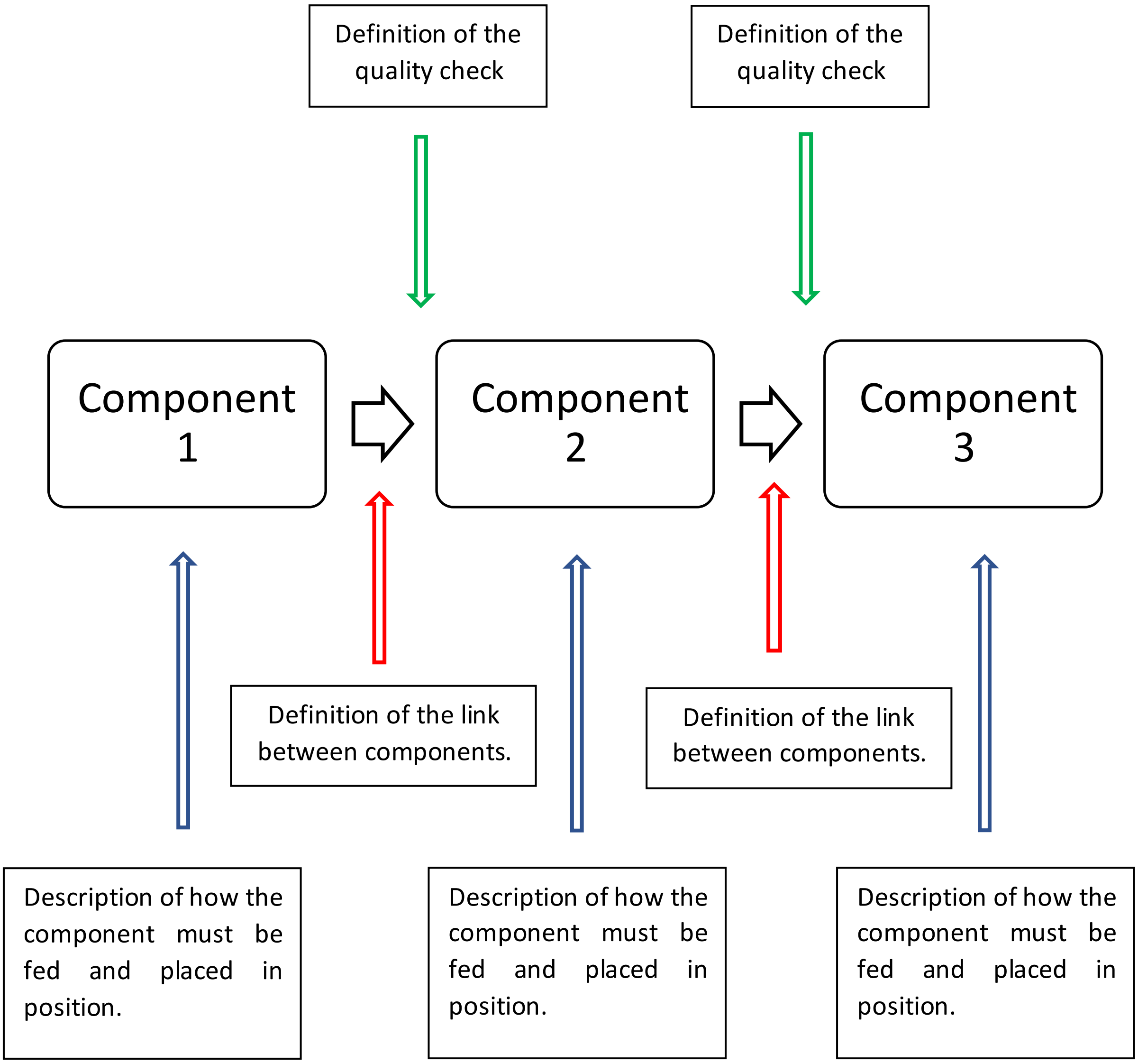


*Figure 16: Process planning*

Starting from the process planning in which all the tasks are defined and described it is possible to understand which are the needed functions by using the assembly functions library previously mentioned.

Once the process planning is defined, the functions needed for each stage of the assembly process are defined and listed.

### 3.2.7 Module selection

After the previous two steps, it is possible to start the module selection.

Therefore, due to the link between the functions and the modules it is possible to understand which are the modules that belongs to the needed function that must be selected.

To properly define an assembly line the mentioned characteristics are required:

- Type of transportation system.
- Type of feeding system.
- Type of modules.
- Quantity of modules to satisfy the required throughput.

To perform this selection different criteria must be considered for each type of modules.

The steps that must be performed to select each module are explained and then formalized in a table.

First, the selection of the type of conveyor must be performed, there are 2 possible alternatives: linear conveyor or rotary table.
This choice is related to the number of operations that must be performed and to the available space in the facility.
Moreover, this choice is related to the need of duplication of modules to satisfy the required throughput, in fact with a linear conveyor higher throughput can be reached respect to adoption of a rotary table. Therefore, if there is the necessity to duplicate modules to satisfy the minimum required throughput, a linear conveyor must be used because in a rotary table layout is not possible to have parallel stations.

Second, a feeding operation must be performed. For small components, a vibratory feeder can be used, while for larger components, the feeding operation can be performed by an operator that puts in place the components before the pick and place.

Third, the pick and place of the fed components must be performed.

Fourth, the link between components must be analysed, this is important to understand the reciprocal position of the pieces and the technology that must be used (screwing or riveting or welding or gluing for example).

Fifth, it is important to identify the modules related to quality check.

All these steps can be summarized in a table that can be used as a guidance for module selection.

|  | CATEGORY | OPTIONS | CRITERIA | DESCRIPTION |
|---|---|---|---|---|
| 1 | Transportation | Linear conveyor | Number of operations > 6 | Bigger components, high number of operations, high space needed between stations. |
|  |  | Rotary table | Number of operations < 11<br>Dimension of the components < 20cm | Smaller components, simple operations, lower number of operations, smaller floor space needed. |
| 2 | Feeding | Vibratory feeder | Dimension of the components < 20cm | Compact components. Considering the dimensions of the component the proper feeder is chosen. |
|  |  | Manual feeding | Dimension of the components > 20cm | Bigger or heavier components. |
| 3 | Pick and place | Robot | 3D movement<br>TH < 2000 pieces/hour | Dimensions of the components and environmental constraints must be considered. |
|  |  | Cam | 2D movement<br>TH < 4000/5000 pieces/hour |  |
|  |  | Arm | 2D movement<br>TH < 3000/3500 pieces/hour |  |
| 4 | Joining | Screwing | CAD | The CAD of the product must be considered to define the process needed. |
|  |  | Riveting | CAD |  |
|  |  | Welding | CAD |  |
|  |  | Glueing | CAD |  |
|  |  | Clinching | CAD |  |
|  |  | Shrinking | CAD |  |
| 5 | Quality check | Visual inspection | Dimension, surface quality, position, presence check. | Quality requirements provided by the client. |
|  |  | Functional inspection | Force or torque to check functionality. |  |
|  |  | Contact inspection (non destructive) | Force to check strength. |  |
|  |  | Contact inspection (destructive) | To check tear strength. |  |

*Table 7: Module selection criteria*

The list of steps before mentioned has been implemented in Matlab to create an automatic system that performs the modules selection returning as output a valid configuration for each of the lines identified during the process planning.

The script is reported in Annex1, in this section the required inputs and the outputs are presented.

Inputs given by the client:

- Maximum available length of the line (only in case of linear conveyor): this data is required to understand if the identified solution respects this constraint.
- Minimum throughput that must be guaranteed.
- Maximum dimension of the component: this data is required to understand if a vibratory feeder can be used or if a manual feeding is required
- List of subsequent activities identified during the process planning.

The script contains all the functions and all the modules that can be used to perform the line configuration.

Output obtained by the script:

- Type of conveyor (linear conveyor or rotary table).
- Type of feeding system.
- Number of operations.
- List of required modules.
- Number of parallel modules required to satisfy the minimum throughput: the algorithm checks if the required throughput is higher than the throughput of all the single modules in isolation, in this case it automatically computes the number of parallel modules that are required to satisfy the requirement.
- Invalid configuration if the solution does not satisfy the maximum available length of the line.

### 3.2.8 Performance evaluation

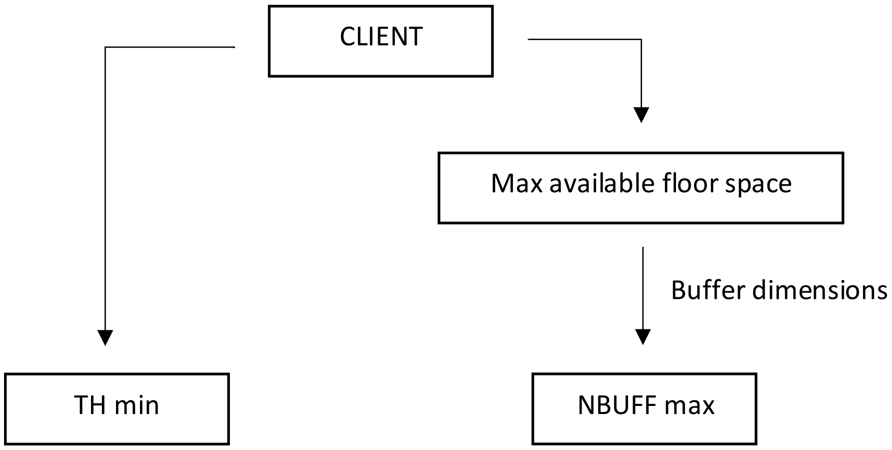
Layout evaluation is necessary to find the best solution from all the possible different solutions obtained up to this point of the configuration process.

First, two main constraints given by the client must be considered: the TH and the maximum available floor space that will be occupied the machine.

The maximum available floor space will be considered to compute the maximum number of buffers that could be allocated in each configuration:

$$NBUFF\,max = \frac{\text{Floor space} - \text{length of modules}}{\text{Size 1 buffer}}$$

The 2 main constraints that will be considered for each configuration are now defined:



Next step is related to the identification of the parameters of the modules, the list of required parameters is provided:

- Cycle time
- MTTF
- MTTR
- Cost.

Moreover, also the cost of 1 unit of buffer must be identified.

Once the module parameters are identified, the following quantities must be computed:

- Production rate: $mu = \frac{1}{\text{Cycle time}}$
- Failure rate: $p = \frac{1}{\text{MTTF}}$
- Repair rate: $r = \frac{1}{\text{MTTR}}$
- Efficiency in isolation: $e = \frac{r}{\text{r+p}}$
- Throughput in isolation: $Rho = mu\ e$

An optimization process can be adopted to define the best possible buffer allocation and to compute the final cost of each alternative.

The approach that will be considered is reported in the figure:

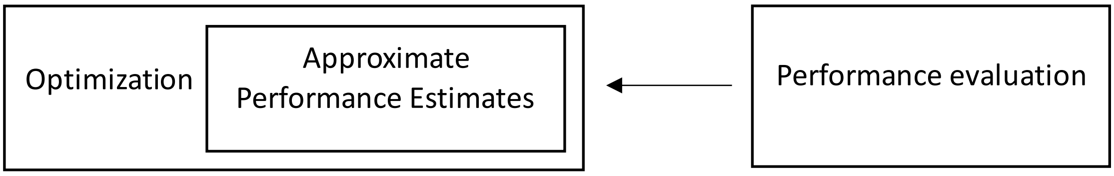


*Figure 17: Optimization algorithm approach*

By implementing this approach for each of the previously found alternatives it will be possible to understand which is the optimal solution that minimizes the cost and satisfies the minimum TH requested by the client.

The steps of the optimization algorithm are now provided:

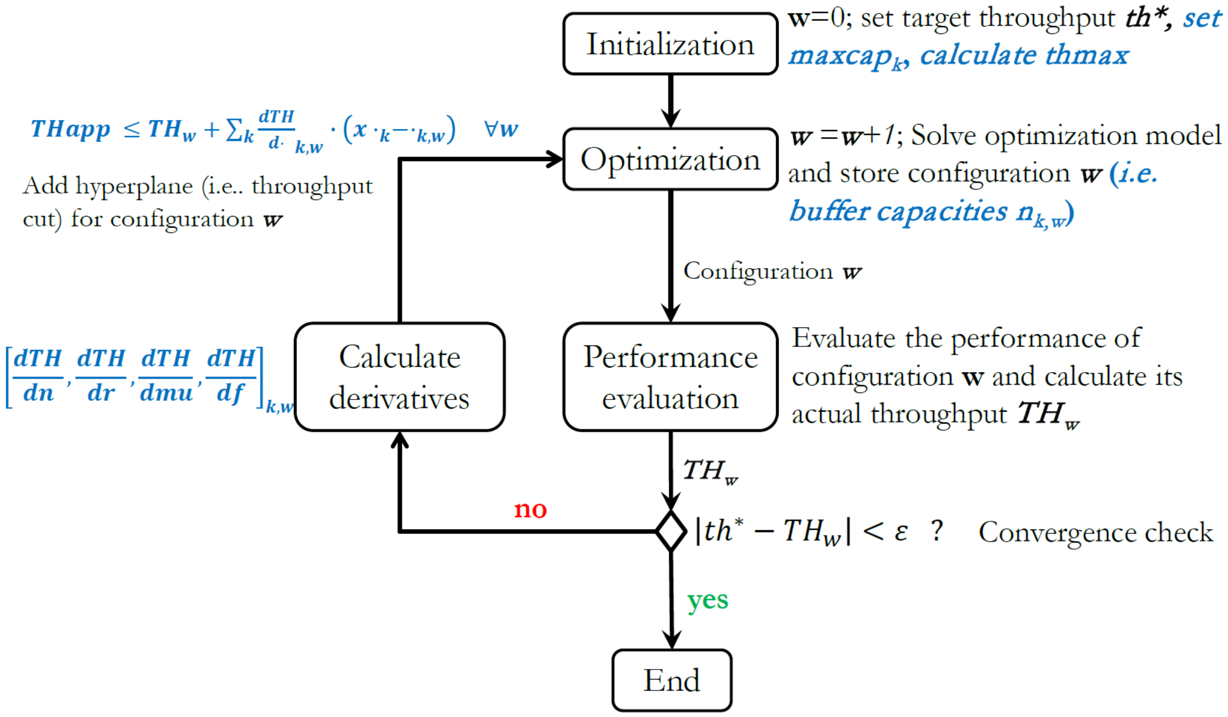


*Figure 18: Optimization algorithm steps*

Given that, due to starvation and blocking phenomena, the actual configuration of the line could not satisfy the requirements, for each station 3 alternatives are considered in which each alternative has a higher number of parallel machines:

1) Initial number: N0
2) N0+1
3) N0+2

The 3 alternatives will be assigned to each stage of the line by using a matrix notation.

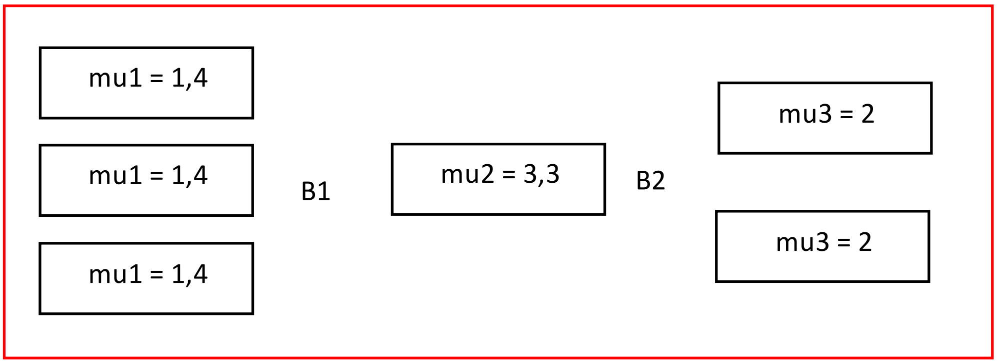
The optimization algorithm will then evaluate the best possible option that satisfies the minimum Th and that has the lowest possible cost.

The inputs of the optimization algorithm include:

- Cost of the modules.
- Cost of the buffers.
- Performances of the modules (production rate, MTTR, MTTF).
- Definition of all the possible alternatives.
- TH that must be guaranteed (called TH star).
- Maximum number of buffers.
- Number of the alternatives.

### 3.3.8.1 Example

Alternative X configuration:



Therefore, the list of alternatives that will be evaluated with the optimization algorithm are:

| | | |
|---|---|---|
| 3 M1 | 1 M2 | 2 M3 |
| 4 M1 | 2 M2 | 3 M3 |
| 5 M1 | 3 M2 | 4 M3 |

Each alternative will be assigned to each stage with a matrix notation:

| STAGE 1 | | | STAGE 2 | | | STAGE 3 | | |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | | | | | | |
| | | | 1 | 1 | 1 | | | |
| | | | | | | 1 | 1 | 1 |

The optimization algorithm will evaluate all the alternatives and it will define which is the best possible one also considering the optimal buffer allocation.

Once for all the alternatives the best configuration is defined, the results will be listed in a table to understand which is the final choice.

N = number of alternatives.
m = number of stations -1.

| ALTERNATIVE | TOTAL COST | TH | BUFF ALLOCAT. |
|---|---|---|---|
| 1 | C1 | TH1 > TH min | B11-B12-B1m |
| 2 | C2 | TH2 > TH min | |
| … | | | |
| N | Cn | THn > TH min | BN1-B12-BNm |

Therefore, the best alternative will be the one that has the lowest cost.

The process can be synthetized as follows:

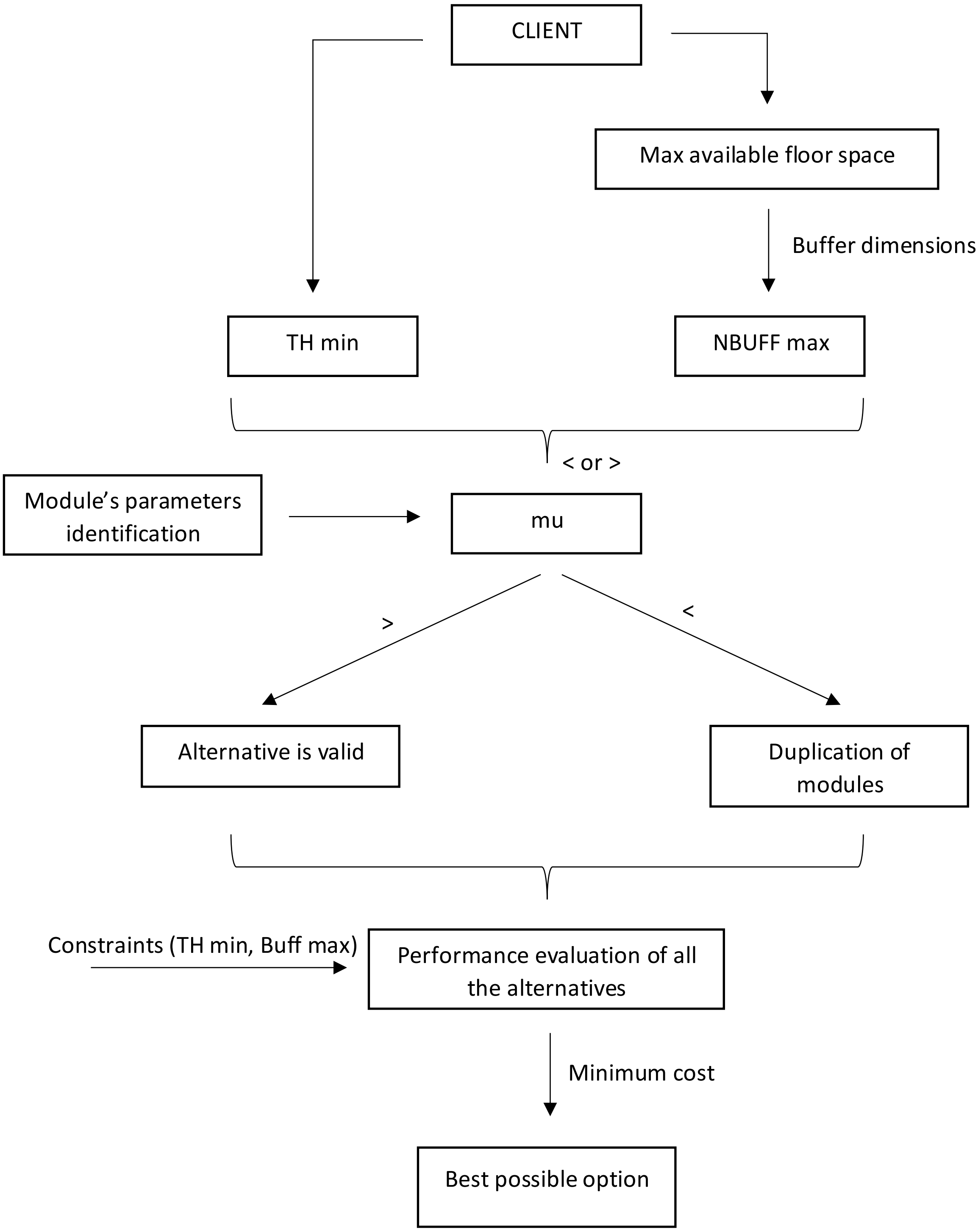


*Table 8: Optimization flow*

### 3.2.9 Upgrade and reconfiguration

Strictly related to the concept of configuration of the machine, upgrade and reconfiguration of machines are other 2 key elements that must be considered for a proper implementation of a PPU business model.

Upgrade is related to the concept of substituting modules or components that compose modules to obtain a better performance of the line (e.g. the client requires and higher throughput), or to introduce advanced technologies (e.g. introduction of brushless motor).

An upgrade to the line does not change the functionalities of the assembly system but it only improves a defined aspect required by the client.

Thanks to the modular structure of a reconfigurable manufacturing system, upgrade operations are possible, and they can represent an additional source of incomes to manufacturers that can respond faster to client requests.

For example, the introduction of a new component to increase quality of the final product or the introduction of a newer PLC to increase the TH can be additional service that must be developed from the after-sale service for the specific customer. This can obviously be achieved given the modularity of the product that can assure an easy upgrade.

Reconfiguration is related to the concept of substituting modules to assembly a similar product, this implies that the client, after a lifecycle is completed, requires a new system to assembly a different variant of the product that was assembled before.

Therefore, reconfiguration is related to substitution or modification to defined modules to respond to a specific need of the client.

## 3.3 Lifecycle analysis of modules

Given that in a PPU business model the machine remains property of the builder, it is essential to establish a process to monitor modules during operations activities and to evaluate the modules after a lifecycle is completed.

To perform a lifecycle analysis, it is required that machines are equipped with sensors for gathering data and subsequent analysis.

These sensors must provide first the number of product that the customer produces because the revenues will be directly related with that index.

Moreover, the machine will be used to extract further data that will be collected by using cloud computing.

These data must be analysed to obtain information regarding the efficiency of the whole system but also the efficiency of the single modules, this is related to the concept of diagnosability of a modular product.

In fact, by implementing a modular diagnostic system, each single module can be analysed to obtain individual information. This cannot be possible in conventional machines that are not composed by identified and individual subcomponents that are the modules.

This diagnostic system can provide information regarding the performances of the single modules and their interaction that can be successively used to introduce improvement actions.

Moreover, to obtain a complete overview of the behaviour of modules, it is necessary to introduce an evaluation system to understand which are the modules that have the highest level of standardization and highest level of residual value.

This can be obtained by analysing the data obtained from the recollection of products from customers, by defining the value of these parameters for each module it will be possible to understand which are the most effective design and it will be possible to obtain a ranking among them.

Not only the level of standardization must be considered, but also the residual value of each component after a period is crucial to be analysed.

In a PPU business model, the manufacturing sytsem will be recollected by the builder after a defined service period to a customer.

Not the entire value of the machine can be expolited for future utilizations once the machine is recollected.

In fact, some parts of the modules, like dedicated fixtures, can’t be standardized while other components must be for sure changed because they are worn-out, or other components like the PLC have to be changed in order to upgrade to the latest version.

Therefore, it can be also useful to obtain a proper classification of the exploitable value of the modules to fully complete the module database with also these information.

A matrix can be composed by considering the percentage of standardization of the module and also the percentage of residual value of the module.
If module 1 has a standardization of 90% because only the 10% is customized and the 70% of the components have infinite life we put a 1 in the corresponding cell of the matrix and the Excel sheet computes automatically the expolitable percentage of the module.

This process is represented in the table below:

| | MODULE 1 | % OF STANDARDIZATION OF THE MODULE | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
| % OF RESIDUAL VALUE | 10 | | | | | | | | | | | |
| | 20 | | | | | | | | | | | |
| | 30 | | | | | | | | | | | |
| | 40 | | | | | | | | | | | |
| | 50 | | | | | | | | | | | |
| | 60 | | | | | | | | | | | |
| | 70 | | | | | | | | | | 1 | |
| | 80 | | | | | | | | | | | |
| | 90 | | | | | | | | | | | |
| | 100 | | | | | | | | | | | |
| | % EXPLOITABLE | 63 | | | | | | | | | | |

*Table 9: Exploitable percentage matrix*

The percentage of standardization can be obtained by the CAD/BOM of the product, in fact by analysing the components of the machinery it is possible to understand which will be the components that will not be suitable for different purposes, like specific fixtures or specific pallets that are developed only for one part family.

Similarly, the percentage of residual value can be obtained by the CAD/BOM of the product by analysing the components that will not guarantee infinite life, like for example pneumatic actuators or bearings.

To obtain the percentage of standardization and residual value, two simple formulas can be used:

$$\%\ of\ standardization = \frac{number\ of\ standard\ components(components\ that\ can\ be\ reused\ for\ different\ purposes)}{total\ number\ of\ components\ of\ the\ module}$$

$$\%\ of\ residual\ value = \frac{number\ of\ failed - worn\ out - old\ components}{total\ number\ of\ components\ of\ the\ module}$$

Once the residual value of each module is obtained, it is possible to introduce a classification of the modules that will explain the level of exploitable percentage of each module.

The classification can be summarized as follows:

| CLASS | NAME | % EXPLOITABLE |
|---|---|---|
| 1 | Super-standard | 75-100% |
| 2 | Standard | 50 - 75% |
| 3 | Low-standard | 25-50% |
| 4 | No-standard | 0-25% |

*Table 10: Class of standardization*

This classification is useful to define a hierarchy of the modules, it is straightforward to understand that modules in class 1 are the most suitable for this type of BM and therefore they can be produced in advance given their high level of standardization and residual value.

By contrast the modules in class 4 are not suitable for this purpose and thus they require modifications.

These values could also be added to the module database to increase the level of details of each module.

By combining all the modules classification, it is possible to obtain a final and comprehensive classification of the whole line that is relevant to understand the as-is situation of the assembly system.
This will tell us if the line under analysis can be suitable or not for a PPU business model and it is a starting point to understand possible improvement actions.

## 3.4 Disassembly and remanufacturing

After the return of a used line to the manufacturer at the end of a lifecycle, the assembly machine must be systematically disassembled into its modules and, if needed, some components or modules can be remanufactured to recover value.

Considering the current industry situation, due to the high level of personalization and interdependencies between components of a single assembly line, it is extremely difficult to re-use assembly plants without the implementation of modularity and standardization in the production phase, as explained in the previous paragraphs.

In fact, the disassembly and remanufacturing phase are strictly correlated to the architecture design phase, because a one-piece machine is not suitable for easy and fast disassembly while, by contrast, a modular machine can be decomposed in its modules without losing value.

This is related to the fact that modularity is not only a key aspect during the composition of a manufacturing line, but it is also a strategic aspect that assures dissasembility.

A modular architecture can decrease interface disjunction difficulty that will lead to reduction of the effort to disconnect, and it can also decrease the risk of damaging while disassembling because the product is designed to be composed and decomposed in a very efficient manner.

Solutions for the inspection, disassembly and remanufacturing of components must be developed inside companies to revamp or substitute the used components; therefore, floor space in the facility and skilled workforce must be acquired to implement a disassembly department in the company.

It can be considered from experimental analysis that a reconfiguration process requires approximately 20% more floor space respect to a normal configuration of a new product.

The disassembly department must be therefore defined and introduced, because disassembly operations are time and workforce intense, as automation is complex to implement.

## 3.5 Monitoring and maintenance

An additional aspect that must be considered is that the machine must be monitored by the builder during the lifecycle to control the value of the product and to assure the maximum possible efficiency.

This was not a problem considering traditional business model, because the machine was property of the client and therefore the machine builder was not interested in controlling the health of the machine or assuring the maximum throughput.

Now, the machine builder must constantly check the state of the machine to solve problems or failure that can damage the machine itself but also that can cause a loss of revenues due to unexploited production capacity that assure the payment of fees from the client.

Therefore, a monitoring system must be developed and mounted on each machine.

More specifically, to obtain a robust and reliable monitoring system it must be developed following modular concepts.

In fact, each module must have its dedicated monitoring system, therefore it is possible to obtain information on the line but also on the single modules.

It is necessary to also develop a Cloud technology that can be used to store data and analyse them by remote. This is a key concept because the builder must constantly check the state and the productivity of its machine.

Moreover, since the machine is property of the builder, the latter will be in charge for the maintenance of the product that will be strictly linked to the monitoring of the product.

In fact, the builder has the knowledge to perform the maintenance at its best to preserve the value of the product, this is also an advantage for the client that does not need to perform any internal maintenance activity that may cause loss of efficiency.

The aspects just reported of monitoring and maintenance are not just a new problem that manufacturers have to deal with, but this is a new opportunity because they can use the gathered data to increase efficiency by performing more precise maintenance operations that will assure increased quality of product or reduction of wasted time by introducing preventive maintenance.

### 3.5.1 Quality – Logistics – Maintenance

Different studies [24] have highlighted the fact that there is a bi-directional mutual cause-effect relation among quality, maintenance, and product logistics.

This link can be an important opportunity to increase le service level of the products developed due to the necessities introduced by PPU.

In fact, it is possible to exploit all the data gathered from the monitoring system to perform a preventive maintenance.

Equipment condition-based preventive maintenance is typically supported by sensorial data collected from the field while the equipment is operational. If these data are properly analysed, they can be used to make inferences about the degradation state of the equipment. This mechanism will allow to identify an undesired state of degradation of the machine and preventive maintenance practices will be promptly activated. This will increase equipment reliability, decreasing the frequency of unexpected random failures and ultimately decreasing corrective maintenance interventions.

Degradation of a component/system is also one of the major factors that cause defective product output. Thus, one conventional solution to reduce the number of defective units, is to conduct preventive maintenance strategies.

Obviously, to perform all the above-mentioned procedures, it is necessary to introduce advanced technologies for on-line data gathering, incorporating as:

- 3D flexible part verification through integration of multi-sensor.

- ICT architectures to support in-line inspection and data sharing at system level.

Given that the product is now sold as a service, companies need to keep in touch with customers during the period of use.

Thus, it is necessary to introduce, if not present, an after-sale department that is necessary to integrate all the information gathered and analysed by the data analysis department.

This department will be necessary to inform the client of possible improving actions for the product, or for the introduction of new maintenance policies.

It will also be useful for upgrade or reconfiguration requests made by customers; in fact, this can be an additional source of revenues for companies.

## 3.6 EOL treatment

The modules and the assembly systems in the pay per use business model remains under the machine tool builder propriety, hence all the problems related to its management are under its responsibility, comprehending the disposal and the end-of-life treatment of modules and different components.

This operation was usually performed by the customers in the traditional business of selling machine tools. In pay-per-use, instead, the contracts and the relationship with the companies managing the disposal of industrial plants must be managed by the machine builder, and a new voice cost must be added. This involves a further interest in the company in the minimization of the industrial waste and the reuse of the modules.

## 3.7 Module management and logistics operations

The systematic return of used plants back to the manufacturer factory increases a lot the intensity of the logistics activity, both related to the transportation and the inventory of modules.

Concerning transportation, in linear business model is mainly composed by the transportation from the manufacturer factory to the customer, whereas considering PPU, the return management must be included, increasing the cost and the complexity of the operations.

Module management and storage is one of the key activities that must be improved to implement the PPU business model, as the obsolescence and the inventory of modules has an important weight both on the economic and on the operational performance of the company. The former is impacted as the modules are considered as fixed assets and the decisions related to their management impact on the ability of the company to be profitable. The latter is affected as new positions and management activities must be implemented. In the as-is situation only some of the new modules are pre produced and stocked in a warehouse, to assemble the line. In the PPU business model, instead, the warehouse space must be increased, as the returned modules are stored until they are able to be employed in different assembly systems.

The complexity of the activity is also increased considering the strategic decision of the module's lifetime. In fact, the storage of modules is related to their requirement in new assembly systems and obsolete modules are less employable. The decisions are also related to the degree of personalization of the modules, namely if the modules are kept in stock as standards or if extra personalization is added to them. Modules in storage can also be revamped by substituting components to increase performances or to perform different activities.

# Chapter 4 – Description of the real case – Cosberg S.P.A.

## 4.1 Company profile

Cosberg S.p.A. is an Italian SME, founded in 1982 by the Viscardi brothers in Terno d'Isola.

They study, design, and build machines and modules to automate the mounting process, the company is leader in the production of assembly plants for many different sectors.

They work in the assembly of furniture accessories like hinges and slides for drawer; in automotive industry for braking system or gearbox; in the electromechanical industry for sockets or switchers; in cosmetic industry; in medical industry; in jewellery industry; in home/office hardware industry like staple remover; in the assembly of tools for hydraulic or pneumatic applications.
The company follows completely the design phase and the realization of the assembly systems that are tailor made for the specific needs of the customer.

The firm works in the B2B (business-to-business) sector, its turnover is around €13 million, and it employs 70 employees.
The firm is part of the "Cosberg Group", composed by Cosberg S.p.A., two European branches (Slovenia and France), one in South America and three partner companies in Italy.

Cosberg S.p.A. is part of different sector associations in Italy, such as "Cluster Tecnologico Fabbrica intelligente", "INTELLIMECH", "AIDAM", "AITEM".

The company is divided in 5 areas, reflecting the phases of the jobs, Business Development, Engineering, Manufacturing, Feeding and Test and General Council. Another department that must be mentioned is the R&D department, with experimental instrumentation, modules, and tools. The innovation activities are also carried on in the other companies of the Group, in a close collaboration.

## 4.2 Products and market

The reference sector of the company is the supply of modules and automatic plants to assemble products and components of different industrial origin.

The solutions produced by the company are highly customized and can produce a wide range of variants of final products. Its machine systems are composed by rotary table, lines, and a combination of the two. The company works on single orders.

Considering the industry in which Cosberg is operating, due to the Covid-19 crisis, in 2020 the production of machine tools, robot and automation in Italy decreased by 24% (4970M€). Exports decreased by 20% with respect to the previous year, and the main country of destination are US, Germany, China, France, and Poland. Italy is the fourth global producer and the fourth exporter in the machine tools sector. Considering 2021, a reverse in the trend is expected with a positive +16% increase in production.

Cosberg since the ’90 expanded its market internationally, especially in Europe, Middle East, US, Brazil and North Africa.

The Italian competitors are both small enterprises, especially in the local market, and middle enterprises, betting especially in innovations and expanding the business. Internationally, the competitors are middle enterprises, mostly located in Germany.

The target market of the company is represented by manufacturing firms of different sectors, as detailed above. Variability, customization, and shorter time to market are the main drivers for the clients of Cosberg and the normal business model used by the company and its competitor is becoming obsolete to satisfy these drivers.

## 4.3 Strategic planning

The shift towards a CE based business model is a topic of huge interest worldwide due to the potential advantages for environment, producers, and customers.

Above all, these new horizons are extremely important for small-medium firms like Cosberg that must innovate continuously to stay ahead of competitors.

Cosberg has therefore developed a strategic plan to develop new possible business, one of them is related to the implementation of a new concept: the servitization of the machines that will allow clients to buy the production capacity that they need when they need, without the purchase of the machine that requires an upfront investment by customers.

To reach this goal, Cosberg has decided to start a research in the field of Pay-per-use that will last for approximately 10 years due to high level of innovation introduced.

It is relevant for the company to follow this trend of innovation related to the concept of servitization because the market has important fluctuations and the life cycle of products is shortening, this means that customers need to buy production capacity only for limited period.

All these aspects explain why Cosberg has decided to follow this trend of innovation.

The strategic plan involves different actions that must be developed to innovate:

- Flexible and reconfigurable systems.
- Monitoring and analysis of performances.
- Predictive maintenance.
- Re-manufacturing and disassembly.
- HMI.
- Automation of the process of reconfiguration of machines.
- Artificial intelligence for automatic failure diagnosis.

Therefore, this new BM will introduce changes in many different functions inside the company that requires focused investments in different fields:

- R&D for design and architecture of machinery.
- After sale department, for monitoring and maintenance.
- Re-manufacturing and disassembly line.
- Financial.

From the technical point of view related to the R&D department, the machines that Cosberg will require for an effective implementation of Pay-per-use, must be reliable, easily reconfigurable, monitorable and upgradable.

Some of these concepts have already been developed by the company, for example with the "Recam" project in which they focused on the fast reconfiguration of machinery.

## 4.4 Modularity and reconfigurability in Cosberg S.P.A – As is situation

Cosberg has already developed some forms of modularity for their products to stay ahead of competitors.

They are starting to introduce the concepts of modularity and standardization to build different modules that can represent the starting point for a future PPU business model introduction.

First, modularity helps them to easily reconfigure a machine to assembly different products contained in a part family. For example, they can assemble on the same line 5 different types of slides for drawers, each with different dimension and features.

Modularity also helps them in the speed introduction of new assembly lines, in fact with the pre-existing modules it is simpler to introduce a new product for a customer. On top of modules only the extremely dedicated parts of the machine, like a specific fixture, must be introduced. This allows them to introduce a new dedicated line for a customer in 4 weeks of work, against months of the competitors.

Another extremely relevant factor for Cosberg is the maintenance and repair of the assembly line, this is related to the fact that a line can produce thousands of products in 1 hour and therefore each minute of downtime can be hugely negative for the customer.
To solve this problem, each module has a specific component that is defined as critical, this means that the components that will fail is identified a priori. Once the critical component is defined, like for example a piston, the module is design to allow the easiest repair. In fact, the scope of the company is to perform a "PIT-STOP" to substitute the critical component. They have designed the module to repair the machine in few seconds without the need of any tool or skill of the operator. This fast repair cannot be performed if there is a single piece extremely complex machine that needs a lot of expertise to be properly repaired.

The last point is related to design information reuse, in fact each module has a so-called GS (standard group) that means that this subsystem is standardized. Once a GS has been used for 3 times, they build a lot of 8/10 GS that will be stored in the warehouse. This is an extremely effective design methodology that helps reducing waste of time for design and for construction.

The 3 main aspects that they are considering to properly define a modular product are:

- Modular mechanical components
- Modular software
- Modular electrical components

# Chapter 5 – Analysis of the real case

## 5.1 Assembly line for hinges

Cosberg produces assembly machines for many different sectors, among them they produce machines to assemble hinges and slides for drawers.

They have produced a line that assembles hinges requested by a customer in 2013, this can be analysed to understand how the whole line is composed by different modules. Moreover, after a new recent request by the same client, the selected line will be modified to assemble new variants of hinges.

This explains how the line can be recollected and reconfigured instead of producing a new one starting from scratch. In fact, the client decided not to buy a brand-new machine but, they decided to buy a reconfigured assembly line, and this is a clear example of circular economy.

Economic advantages: the new line would have cost 3mln euros while the reconfigured line has a maximum cost of 1,5mln. This means that Cosberg will recollect the line, will change defined elements, and will evaluate the state of others to understand if substitution is needed. Therefore, they have defined a maximum price because the process of reconfiguration is at its first stage, and they do not know exactly the state of all the components.

As mentioned before, this will lead to reusage of assembly functions that represent a reduction of structural waste and a limitation of the price of the line, moreover part of the human labour needed to assembly the original machine will not be wasted.

In this work, it will be analysed how a real configuration process can be implemented and, after that, how the line can be reconfigured for a request of the same client for new types of hinges.

## 5.2 Line configuration

The line assembles 4 variants of the hinge reported below:

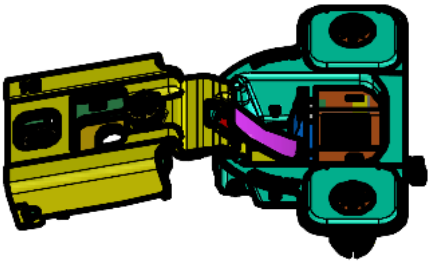


*Figure 19: Hinge to be assembled*

In the following paragraphs the methodology previously explained in chapter 3 to configure a modular assembly line will be applied to the real case.

1. The first step is related to the process planning to define the tasks that must be performed.
2. The second step is to assign each task to a function by using the function library.
3. The third step is related to the selection of the right modules by selecting them from Cosberg database to generate the final line.

### 5.2.1 Process planning

The first step is related to the hierarchical object representation in which the product is decomposed in its subassemblies and in its components, this is important to understand how many lines will be needed to assemble the final product.

The hinge is composed by 2 main subassemblies: the wing and the box that will be assembled on 2 parallel lines.

After than a final line will be needed to assemble the 2 subassemblies.

The hierarchical object representation is reported in figure:

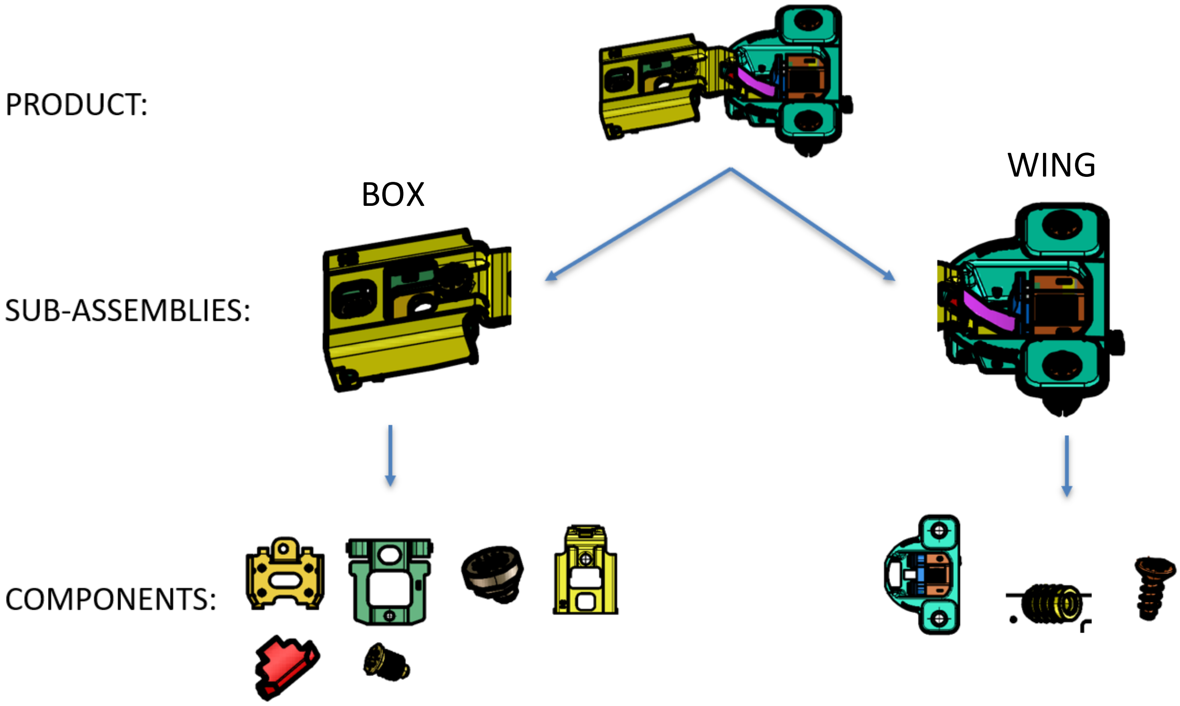


*Figure 20: Hierarchical object representation*

As can be shown by the representation of the product 3 lines will be needed to assemble the product.

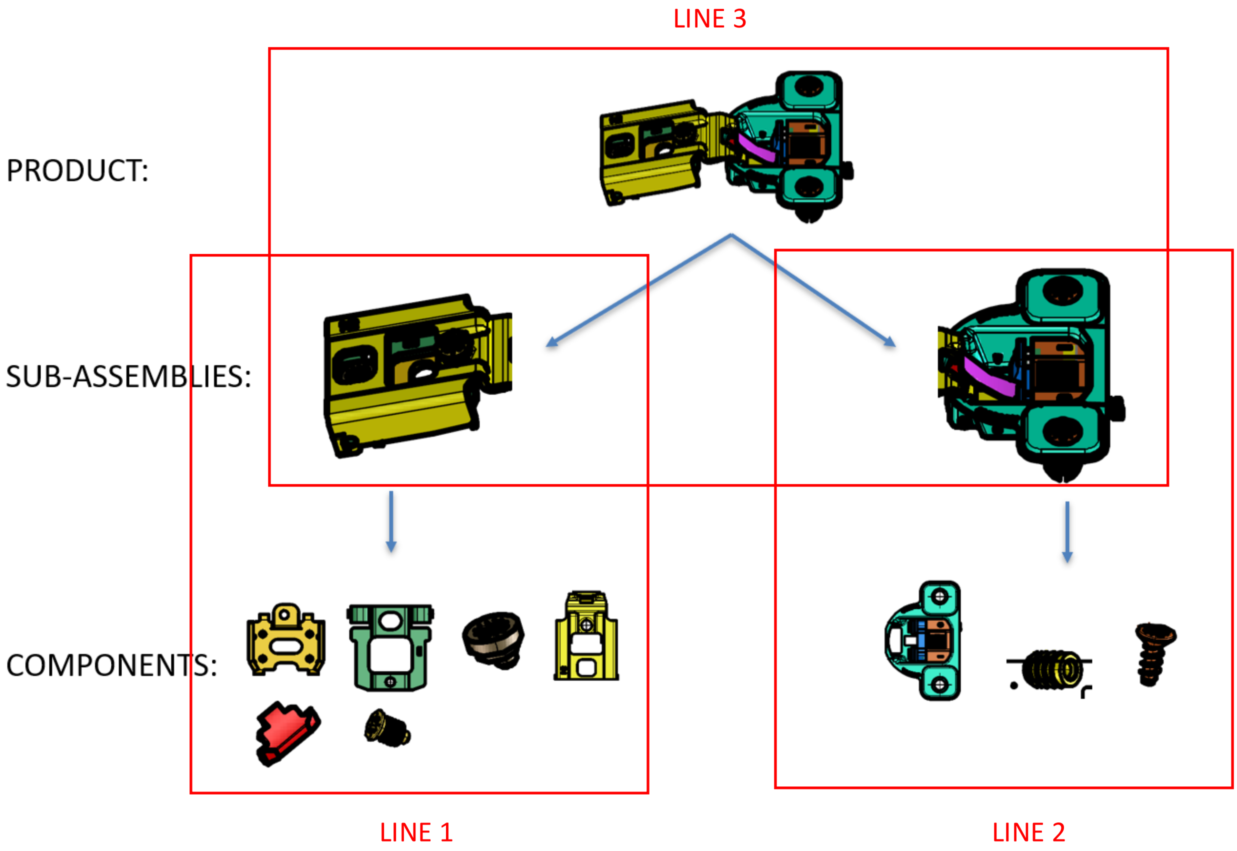


*Figure 21: Number of assembly lines needed*

Once the number of lines has been defined, it is necessary to understand the assembly sequence of all the components, to do that the CAD and the BOM of the product must be considered.

From the CAD of the product, it is possible to understand which are the constraints that tell which component must be assembled first and which last, in this step it is possible that more than one alternative may be found.

In the case of this work, the product that must be assembled has relatively low number of components and the CAD is simple, therefore only one possible alternative for the sequence of the components can be considered.

The assembly sequence of the first subassembly (the BOX) that will be carried out on the first line is now reported in figure:

*Figure 22: Assembly sequence line 1 (BOX)*

As can be seen, components 1 and 2 will be linked by a screw that is component 3, these 3 components will then be linked to component 4 via a screw that is component 5.
The last component that will be inserted one all the others are assembled is component 6.

The assembly sequence of the second subassembly (the WING) that will be carried out on the second line is now reported in figure:

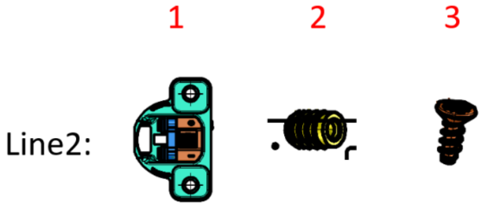


*Figure 23: Assembly sequence line 2 (WING)*

In this subassembly, component 2, which is a dowel, must be inserted in the 2 holes of component 1 and finally component 3 which is a screw is inserted into component 2.

The assembly sequence of the final product that will be carried out on the third line is now reported in figure:

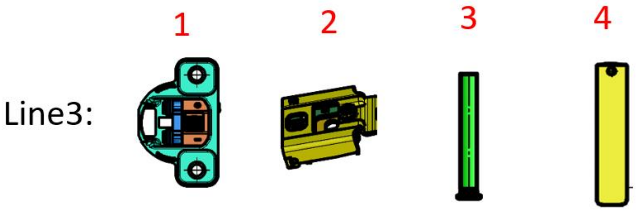


*Figure 24: Assembly sequence line3 (Final product)*

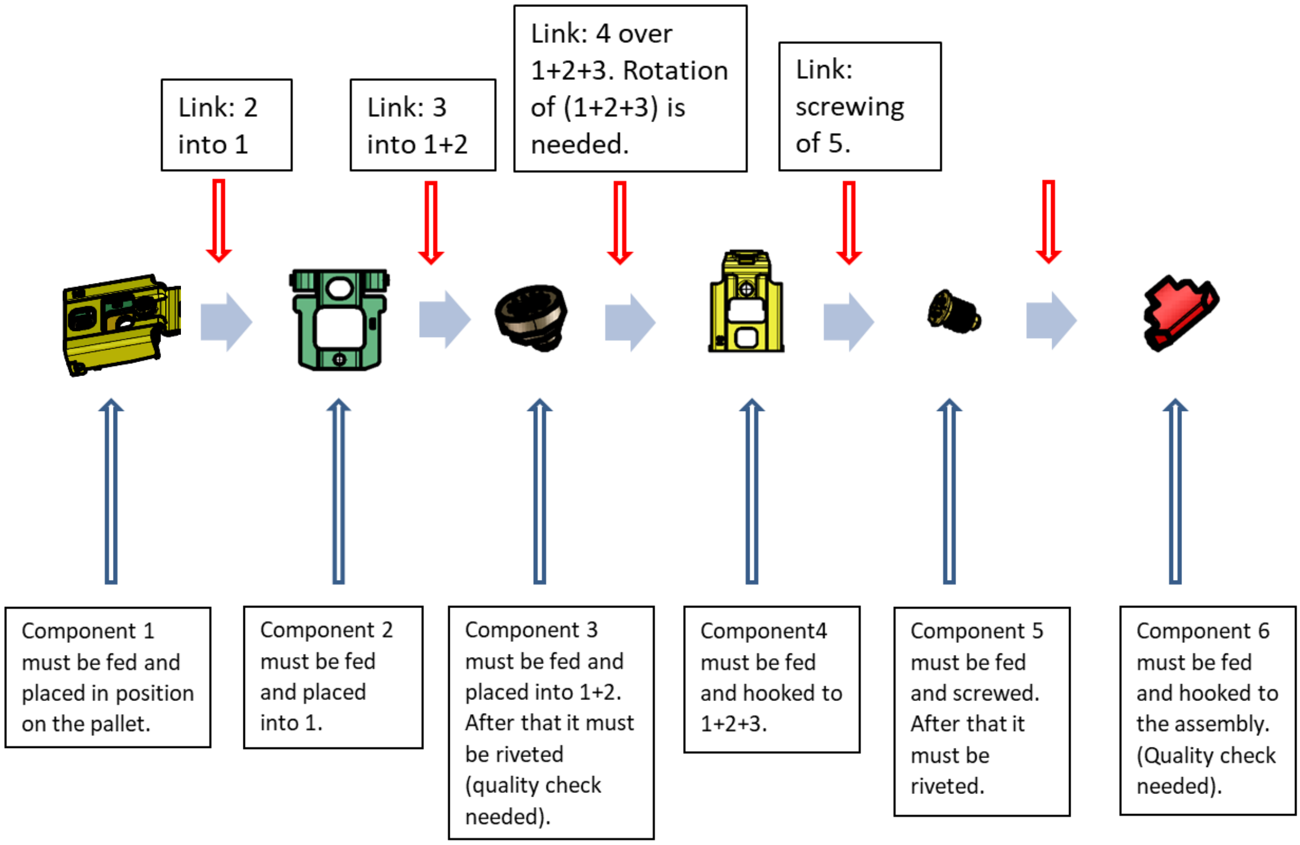
In this assembly phase, components 1 and 2 will be linked by a riveting process by the component 3. Once this operation is performed, the final operation is related to the insertion of the final spring which is component 4.

Once all the assembly sequences have been defined, the next step is related to the logical definition of all the tasks that must be performed, this is a very important step because from the task definition the subsequent assembly functions needed will be extracted.

During this phase, which is the core of the process planning, the logical steps that must be performed for each line are identified and explained.

The tasks need to explain how to feed the components to the line, how to link them and when is needed to perform a quality check.

The tasks of all the lines will now be descripted in the following figures:



Link: 2 into 1

Link: 3 into 1+2

Link: 4 over 1+2+3. Rotation of (1+2+3) is needed.

Link: screwing of 5.

Component 1 must be fed and placed in position on the pallet.

Component 2 must be fed and placed into 1.

Component 3 must be fed and placed into 1+2. After that it must be riveted (quality check needed).

Component4 must be fed and hooked to 1+2+3.

Component 5 must be fed and screwed. After that it must be riveted.

Component 6 must be fed and hooked to the assembly. (Quality check needed).

*Figure 25: Task description line 1*

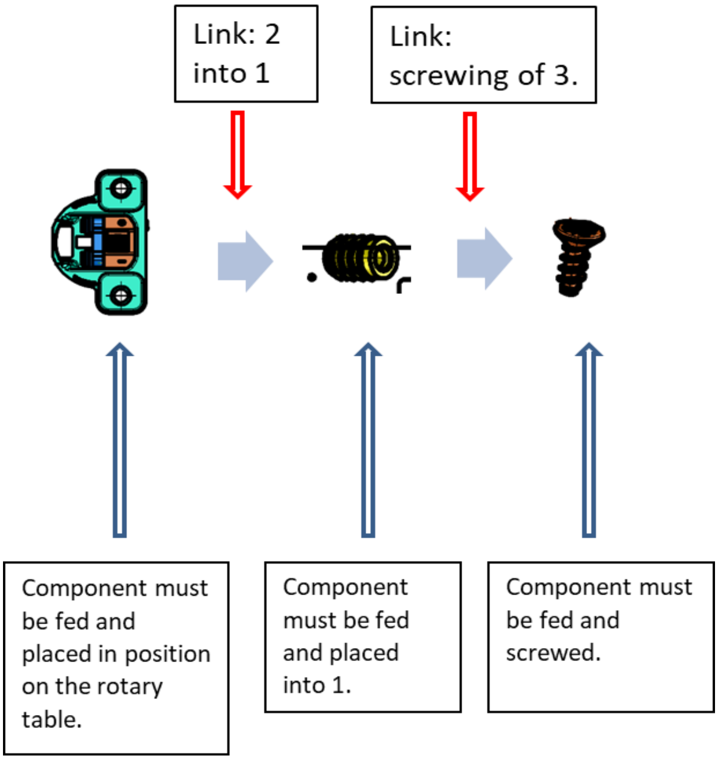


*Figure 26: Task description line 2*

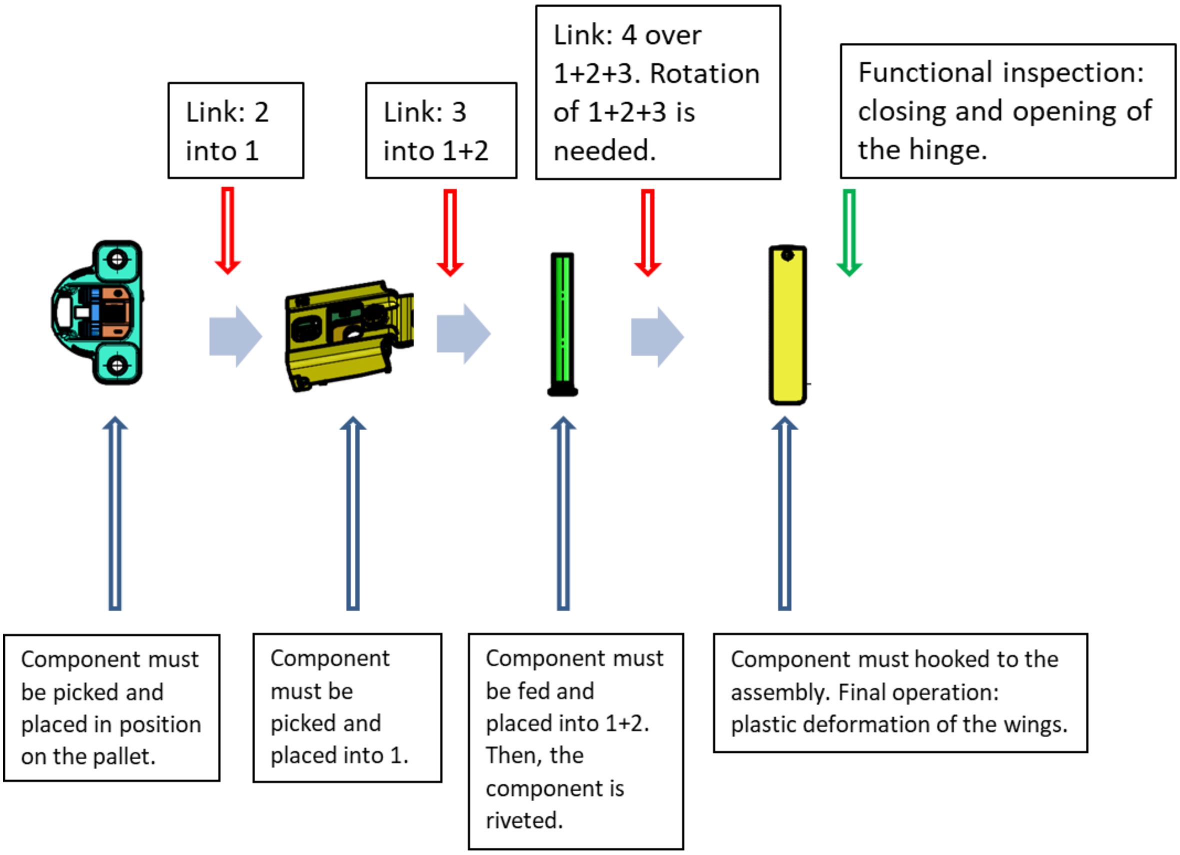


*Figure 27: Task description line 3*

### 5.2.2 Assembly functions library

Starting from the process planning and by using the functions library, it is possible to assign to each task a function.

In the table below all the possible functions that constitute the functions library are listed:

| ASSEMBLY PROCESSES |
|---|
| Classes: |
| TRANSPORTATION |
| Linear conveyor |
| Rotary table |
| PICK and PLACE |
| 2D (cam) |
| 2D (arm) |
| 3D (robot) |
| JOINING |
| Screwing |
| Riveting |
| Welding |
| Soldering |
| Shrinking |
| Gluing |
| Clinching |
| PLASTIC DEFORMATION |
| Bending |
| MATERIAL REMOVAL |
| Tapping |
| FEEDING |
| Vibratory feeding system |
| Manual feeding |

*Table 11: Assembly functions library*

| INSPECTION: |
|---|
| Presence |
| Inductive sensor |
| Capacitive sensor |
| Optic sensor |
| Magnetic sensors |
| Vision system |
| Position/distance |
| Optic sensor |
| Ultrasound sensor |
| Vision system |
| Shape |
| Vision system |
| Surface finishing |
| Vision system |
| Contact (Non destructive) |
| Strength |
| Contact (Destructive) |
| Tear strength |
| Functional |
| Linear actuation |
| Torque |

*Table 12: Quality check functions library*

## 5.2.3 Cosberg Modules library

A list of all the standard modules produced by Cosberg linked to their functions is now provided:

| COSBERG STANDARD MODULES DATABASE | | | |
|---|---|---|---|
| IDENTIFICATION | FUNCTION | TH (pieces/hour) | NOTES |
| MODULE 0_1 | Piezoelectric Vibratory feeding system (linear) | 3000 | Different sizes available. |
| MODULE 0_2 | Electromagnetic Vibratory feeding system (circular) | 8000 | Required for all the Vibratory feeding systems. |
| MODULE 1_1 | Pick and place (Arm-2D) | 3600 | |
| MODULE 1_2 | Pick and place (Cam-2D) | 5000 | |
| MODULE 1_3 | Pick and place (Robot-3D) | 2000 | |
| MODULE 2_1 | Screwing (electric) | 3600 | Bosch motor |
| MODULE 2_2 | Screwing (penumatic) | 3600 | FIAM Pneumatic motor |
| MODULE 3 | Riveting | 3600 | Bosch motor |
| MODULE 10 | Tapping | 3600 | Bosch motor |
| MODULE 11_1 | Functional inspection (Linear actuator - 100N) | 4800 | DC24 V |
| MODULE 11_2 | Functional inspection (Linear actuator - 200N) | 2400 | DC24 V |
| MODULE 11_3 | Functional inspection (Linear actuator - 500N) | 1200 | DC24 V |
| MODULE 12 | Disentangle and feeder for springs | 3600 | |
| MODULE 13 | Press | 3600 | Bosch motor |

*Table 13: Cosberg standard modules library*

Considering the before mentioned list of functions, the modules that are not currently produced by Cosberg are:

| OUTSOURCED MODULES DATABASE | |
|---|---|
| IDENTIFICATION | FUNCTION |
| MODULE 4 | Welding |
| MODULE 5 | Soldering |
| MODULE 6 | Shrinking |
| MODULE 7 | Gluing |
| MODULE 8 | Clinching |
| MODULE 9 | Bending |
| MODULE 14 | Presence inspection |
| MODULE 15 | Dimension inspection |
| MODULE 16 | Vision system |
| MODULE 17 | Lubrication system |
| MODULE 18 | Calibration system |

*Table 14: Outsourced modules*

## 5.2.4 Task – Function link

Once all the tasks that must be performed have been identified during the process planning, it is necessary to link each task to a given function.

The list of all the task and their relative functions are now listed:

| TASK | DESCRIPTION | FUNCTION |
|---|---|---|
| 1 | The base of the hinge must be fed to the line and must be put on the pallet of the conveyor. | Feeding + pick and place. |
| 2 | The adjustment plate must be fed to the line and put in the base. | Feeding + pick and place. |
| 3 | The eccentric pin must be fed to the line and inserted on plate+base. | Feeding + moving. |
| 4 | The eccentric pin must be riveted. | Riveting. |
| 5 | The eccentric pin must be checked by an actuator to verify the riveting process. | Contact inspection. |
| 6 | The subgroup of components must be 180° rotated and put on the pallet. | Pick and place. |
| 7 | The wing of the hinge must be fed to the line and linked to the base. | Feeding + pick and place. |
| 8 | The screws of the subgroup must be fed and screwed. | Screwing. |
| 9 | The screws must be riveted. | Riveting. |
| 10 | The eccentric pin must be checked by a linear actuator to verify the riveting process. | Functional inspection. |
| 11 | The cam must be fed to the line and linked to the wing. | Feeding + pick and place. |
| 12 | The wing subgroup must be put on a linear transportation system to reach station 2B. | Pick and place. |

*Table 8: Wing's tasks description*

| TASK | DESCRIPTION | FUNCTION |
|---|---|---|
| 1 | The box must be fed to the rotary table and put in a specified position. | Feeding + pick and place. |
| 2 | 2 dowels must be fed to the mounting equipment.  2 screws are put in the dowels and screwed. | Feeding + screwing. |
| 3 | The presence of the dowels must be checked. | Visual inspection. |
| 4 | The box is put on the pallet. | Pick and place. |

*Table 9: Box's tasks description*

| TASK | DESCRIPTION | FUNCTION |
|---|---|---|
| 1 | The box must be picked and placed on the pallet. | Pick and place. |
| 2 | The wing is rotated and placed in an intermediate buffer. The wing is then placed inside the box while a rivet is placed in the hole. | Pick and place. |
| 3 | Riveting. | Riveting. |
| 4 | Two springs must be fed to the subgroup. | Feeding + pick and place. |
| 5 | The spring must be fed and put in place. | Feeding + pick and place. |
| 6 | The hinge must be closed and the number of springs must be checked. | Functional and visual inspection. |
| 7 | The riveting must be checked. | Visual inspection. |
| 8 | The hing must be picked and placed and the wings of the hinge must be bended. | Pick and place + bending. |
| 8 | The hinge must be placed in an intemediate buffer to verify correct functioning mechanism. After that, the hinges is delivered. | Pick and place +functional inspection. |

*Table 10: Final assembly tasks description*

## 5.2.3 Selection of the needed modules

Each function has been assigned to a corresponding module; therefore, it is possible to assign to each station of the line the required module.

This paragraph is related to the selection of the modules that will compose the assembly line.

As an example, once it is defined that a pick and place function is needed, the next step is the definition of the right type of pick and place that can be a cam or an arm or a robot.

Similarly, if a transportation function is needed, it is important to define which type between a linear conveyor, or a rotary table is the best option.

To perform this task, a table that considers different constraints has been developed, this can be used as a guide to make the final precise choice of the module that belongs to the same class of modules.

The table that has been presented in chapter 3 is considered and reported:

| | CATEGORY | OPTIONS | CRITERIA | DESCRIPTION |
|---|---|---|---|---|
| 1 | Transportation | Linear conveyor | Number of operations > 6 | Bigger components, high number of operations, high space needed between stations. |
| | | Rotary table | Number of operations < 11<br>Dimension of the components < 20cm | Smaller components, simple operations, lower number of operations, smaller floor space needed. |
| 2 | Feeding | Vibratory feeder | Dimension of the components < 20cm | Compact components. Considering the dimensions of the component the proper feeder is chosen. |
| | | Manual feeding | Dimension of the components > 20cm | Bigger or heavier components. |
| 3 | Pick and place | Robot | 3D movement<br>TH < 2000 pieces/hour | Dimensions of the components and environmental constraints must be considered. |
| | | Cam | 2D movement<br>TH < 4000/5000 pieces/hour | |
| | | Arm | 2D movement<br>TH < 3000/3500 pieces/hour | |
| 4 | Joining | Screwing | CAD | The CAD of the product must be considered to define the process needed. |
| | | Riveting | CAD | |
| | | Welding | CAD | |
| | | Glueing | CAD | |
| | | Clinching | CAD | |
| | | Shrinking | CAD | |
| 5 | Quality check | Visual inspection | Dimension, surface quality, position, presence check. | Quality requirements provided by the client. |
| | | Functional inspection | Force or torque to check functionality. | |
| | | Contact inspection (non destructive) | Force to check strength. | |
| | | Contact inspection (destructive) | To check tear strength. | |

*Table 15: Precise module selection*

To automatically perform the module selection process, a Matlab script (reported in Annex 1) has been used.

The script gives as output:

- Type of conveyor.
- Type of feeding system.
- Type of module.
- Number of parallel modules required to satisfy the minimum throughput.

The following tables describe how the stations of the line have been composed by the selected modules to perform the identified tasks.

| ASSEMBLY LINE 1 - Linear conveyor | | |
|---|---|---|
| NAME | FUNCTION | MODULES |
| STATION 1A | Feeding + pick and place. | 0_1 + 1_1 |
| STATION 1B | Feeding + pick and place. | 0_1 + 1_1 |
| STATION 1D | Feeding + pick and place(cam) + lubrication. | 0_1 + 1_2 + 17 |
| STATION 1E | Riveting. | 3 |
| STATION 1F | Functional inspection. | 11 |
| STATION 1G | Pick and place +lubrication. | 1_1 + 17 |
| STATION 1H | Feeding + pick and place + lubrication. | 0_1 + 1_1 + 17 |
| STATION 1I | Feeding + Screwing. | 0_1 + 7 |
| STATION 1L | Riveting. | 5 |
| STATION 1M | Functional inspection. | 11 |
| STATION 1N | Feeding + pick and place(cam). | 0_1 + 1_2 |
| STATION 1P | Pick and place + presence inspection. | 1_1 + 14 |

*Table 16: Assembly line 1*

| ASSEMBLY LINE 2 - Rotary table | | |
|---|---|---|
| NAME | FUNCTION | MODULES |
| STATION A1 | Feeding + pick and place + presence inspection. | 0_1 + 1_1 + 14 |
| STATION A4 | Feeding + screwing. | 0_1 + 2 |
| STATION A6 | Presence inspection. | 14 |
| STATION A8 | Pick and place. | 1_1 |

*Table 17: Assembly line 2*

| ASSEMBLY LINE 3 - Linear conveyor | | |
|---|---|---|
| NAME | FUNCTION | MODULES |
| STATION 2A | Lubrication + pick and place. | 17 + 1_1 |
| STATION 2B | Feeding + pick and place + pick and place. | 0_1 + 1_1 + 1_1 |
| STATION 2B | Feeding + pick and place. | 0_1 + 1_1 |
| STATION 2C | Riveting. | 3 |
| STATION 2N | Feeding + pick and place + lubrication. | 0_1 + 1_1 + 17 |
| STATION 2D | Feeding + pick and place + lubrication. | 0_1 + 1_1 + 17 |
| STATION 2E | Presence inspection. | 14 |
| STATION 2H | Presence inspection. | 14 |
| STATION 2L | Pick and place + bending. | 1_1 + 9 |
| STATION 2L | Pick and place 3D + functional inspection. | 1_3 + 11 |

*Table 18: Assembly line 2*

Once all the modules have been assigned to the stations the layout can be synthetized.

The following figure shows how the whole configuration process has been implemented to reach the final assembly line configuration:

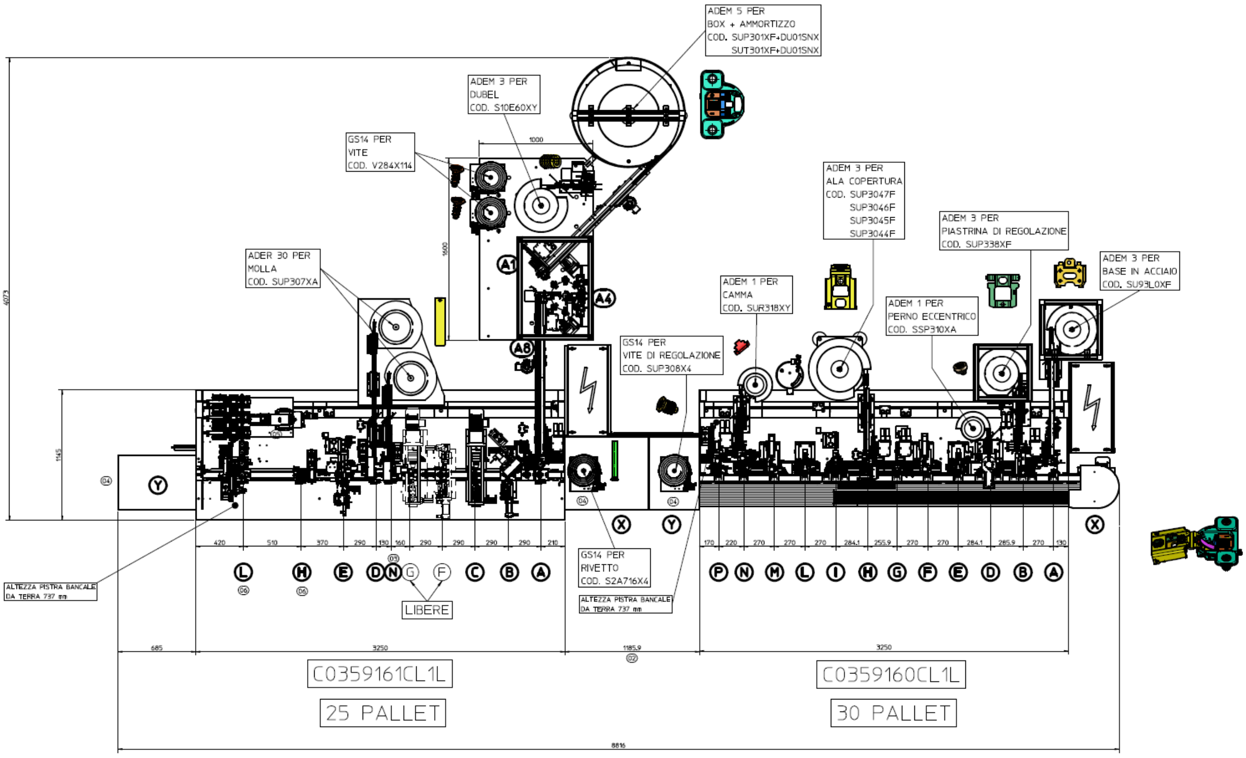


*Figure 28: Assembly line layout*

As can be seen in the figure below, there are 3 separate assembly lines, line 1 and 2 for the subassemblies and line 3 for the final assembly:

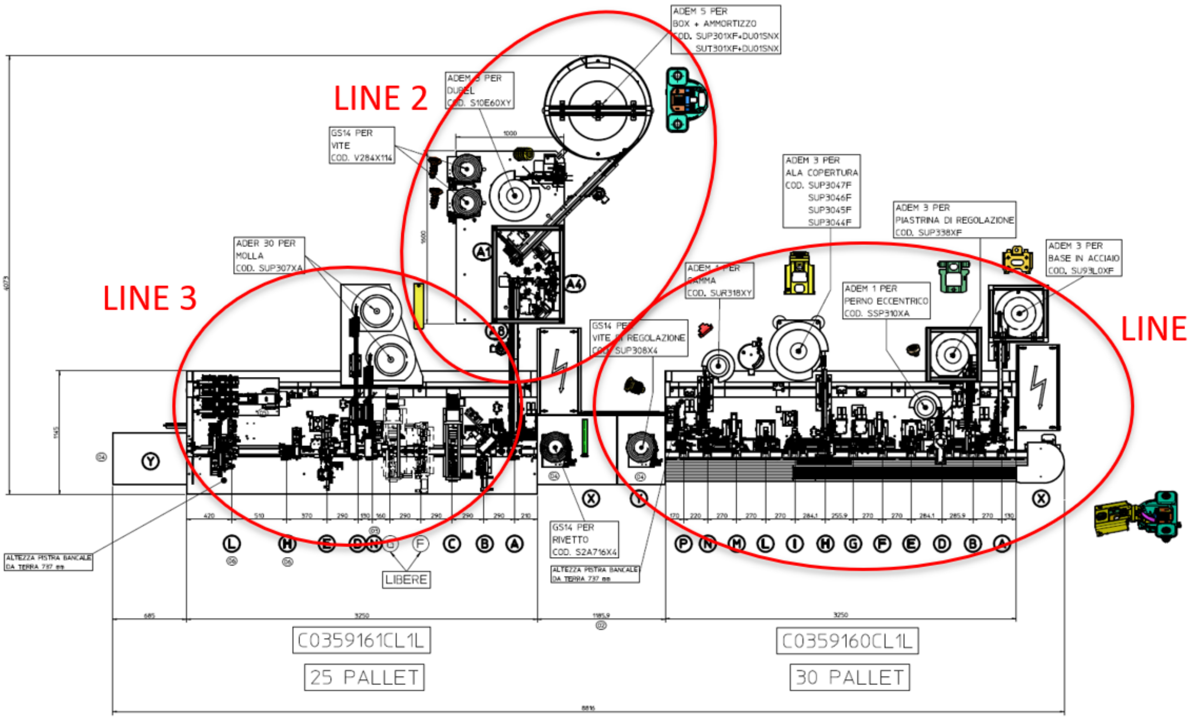


Figure 29: Assembly line composition

Moreover, it is possible to see how all the needed modules have been inserted in the line following the precise process planning that has been developed.

## 5.3 Additional line analysed

Four additional assembly lines have been analysed to validate the Matlab script and to obtain a classification of the used modules, to understand which are the most and less used. This classification can be a starting point for future introduction of new standard modules in Cosberg S.p.a. and to understand which are the key modules.

### 5.3.1 Product 2

The product that must be assembled by this assembly line is a slide hinge:

*Figure 30: Product to be assembled 2*

To assemble this product 2 different lines (Line 4 and Line 5) are required, in the following tables the modules, that have been obtained from the selection algorithm, are listed.

| ASSEMBLY LINE 4 - Rotary table | | |
|---|---|---|
| NAME | FUNCTION | MODULES |
| STATION A1 | Feeding + pick and place. | 0_1 + 1_1 |
| STATION B4 | Lubrication. | 17 |
| STATION C5 | Tapping + lubrication. | 10 + 17 |
| STATION D7 | Screwing + presence inspection. | 2 + 14 |
| STATION E9 | Bending. | 9 |
| STATION F11 | Feeding + Lubrication + Pick and place (cam). | 0_1 + 17 + 1_2 |
| STATION G13 | Feeding + pick and place. | 0_1 + 1_1 |
| STATION H15 | Riveting. | 3 |
| STATION I16 | Pick and place. | 1_1 |
| STATION L17 | Calibration. | 18 |
| STATION M22 | Pick and place | 1_1 |

*Table 19: Line 4 - modules*

| ASSEMBLY LINE 5 - Linear Conveyor | | |
|---|---|---|
| NAME | FUNCTION | MODULES |
| STATION A | Pick and place. | 1_1 |
| STATION B | Lubrication. | 17 |
| STATION C | Feeding + pick and place. | 0_1 + 1_1 |
| STATION C | Feeding + pick and place. | 0_1 + 1_1 |
| STATION C | Pick and place. | 1_1 |
| STATION C | Feeding. | 0_1 |
| STATION C | Feeding(spring) + Lubrication + pick and place. | 13 + 17 + 1_1 |
| STATION C | Feeding + pick and place. | 0_1 + 1_1 |
| STATION D | Riveting. | 3 |
| STATION E | Pick and place + Feeding + pick and place (cam). | 1_1 + 0_1 + 1_2 |
| STATION E | Feeding + Pick and place + Dimension inspection. | 0_1 + 1_1 + 15 |
| STATION F | Riveting. | 3 |
| STATION G | Lubrication. | 17 |
| STATION H | Feeding + pick and place. | 0_1 + 1_1 |
| STATION I | Pick and place(cam)+Lubrication. | 1_2 + 17 |
| STATION L | Presence inspection + Functional inspection. | 14 + 11 |
| STATION M | Pick and place | 1_1 |

*Table 20: Line 5 - modules*

## 5.3.2 Product 3

The product that must be assembled by this assembly line is a base for hinge support:

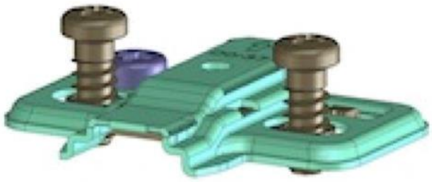


*Figure 31: Product to be assembled 3*

To assemble this product 1 line (Line 6) is required, in the following table the modules, that have been obtained from the selection algorithm, are listed.

| ASSEMBLY LINE 6 - Rotary table | | |
|---|---|---|
| NAME | FUNCTION | MODULES |
| STATION A1 | Feeding + Pick and place. | 0_1 + 1_1 |
| STATION B2 | Lubrication. | 17 |
| STATION C3 | Feeding + pick and place(cam). | 0_1 + 1_2 |
| STATION D5 | Feeding + pick and place. | 0_1 + 1_1 |
| STATION E6 | Riveting. | 3 |
| STATION F7 | Bending. | 9 |
| STATION G9 | Functional inspection. | 11 |
| STATION H10 | Feeding + screwing. | 0_1 + 2 |
| STATION L12 | Presence inspection. | 14 |

*Table 21: Line 6 - modules*

### 5.3.3 Product 4

The product that must be assembled by this assembly line is a clip:

*Figure 32: Product to be assembled 4*

To assemble this product 1 line (Line 7) is required, in the following table the modules, that have been obtained from the selection algorithm, are listed.

| ASSEMBLY LINE 7 - Linear Conveyor | | |
|---|---|---|
| NAME | FUNCTION | MODULES |
| STATION A | Feeding + pick and place. | 0_1 + 1_1 |
| STATION B | Feeding + pick and place. | 0_1 + 1_1 |
| STATION C | Feeding + pick and place. | 0_1 + 1_1 |
| STATION D | Presence inspection + riveting. | 14 + 3 |
| STATION E | Vision system. | 16 |
| STATION F | Functional inspection. | 11 |

*Table 22: Line 7 - modules*

In this case, the algorithm provides as a result the selection of a rotary table due to the low number of operations involved.

The rotary table options cannot be feasible if the throughput that must be satisfied requires a duplication of modules (parallel solution).

## 5.3.4 Results of the analysis

A total of 7 different assembly lines that contains a total of 142 modules have been analysed in this work.

The following table represents the quantity of each module in the different lines, a composition index has been introduced to understand the percentage of composition of the lines.

| | LINE 1 | LINE 2 | LINE 3 | LINE 4 | LINE 5 | LINE 6 | LINE 7 | TOT | COMPOSITION INDEX % |
|---|---|---|---|---|---|---|---|---|---|
| MODULE 0_1 | 6 | 2 | 4 | 3 | 7 | 4 | 3 | 29 | 20,42 |
| MODULE 0_2 | 6 | 2 | 4 | 3 | 7 | 4 | 3 | 29 | 20,42 |
| MODULE 1_1 | 5 | 2 | 6 | 5 | 9 | 2 | 3 | 32 | 22,54 |
| MODULE 1_2 | 2 | | 1 | | 2 | 1 | | 6 | 4,23 |
| MODULE 1_3 | | | 1 | | | | | 1 | 0,7 |
| MODULE 2 | | 1 | | 1 | | 1 | | 3 | 2,11 |
| MODULE 3 | 1 | | 1 | 2 | | 1 | 1 | 6 | 4,23 |
| MODULE 4 | | | | | | | | 0 | 0 |
| MODULE 5 | 1 | | | | | | | 1 | 0,7 |
| MODULE 6 | | | | | | | | 0 | 0 |
| MODULE 7 | | | | | | | | 0 | 0 |
| MODULE 8 | | | | | | | | 0 | 0 |
| MODULE 9 | | | 1 | | | 1 | | 2 | 1,41 |
| MODULE 10 | | | | | | | | 0 | 0 |
| MODULE 11 | 2 | | 1 | | 1 | 1 | 1 | 6 | 4,23 |
| MODULE 12 | | | | | | | | 0 | 0 |
| MODULE 13 | | | | | 1 | | | 1 | 0,7 |
| MODULE 14 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 9 | 6,34 |
| MODULE 15 | | | | | 1 | | | 1 | 0,7 |
| MODULE 16 | | | | | | | 1 | 1 | 0,7 |
| MODULE 17 | 3 | | 3 | 3 | 4 | 1 | | 14 | 9,86 |
| MODULE 18 | | | | 1 | | | | 1 | 0,7 |
| TOT | 27 | 9 | 24 | 19 | 33 | 17 | 13 | 142 | |

*Table 23: Module usage*

As shown in the table, the most important and common modules are the feeding and pick and place (2D-arm) modules that cover more than 60% of the total.
These modules, that are the most used and therefore the most important to start an implementation of a PPU BM, are already produced by Cosberg.

The module that covers the 10% of the total is Module 17 (Lubrication system) that is not currently internally produced, this can be considered as a future upgrade of the internally produced modules. This implies that a possible standardization of this type of module could be useful because this module can be reused in different lines for different clients.

After that, the module that covers 6,34% of the total is Module 14 (Presence inspection) that is not currently produced internally. The same reasoning defined for Module 17 can apply.

Then, modules 3 (riveting) and 10 (tapping) cover 4% of the total and they are internally produced by the firm.

Different modules have not been used in the analysed lines: modules 4,6,7,8,12. Therefore, these modules are not extremely important for a PPU implementation because they will not be reused in different lines, thus they can be outsourced when required for specific cases.

## 5.4 Line reconfiguration

In this chapter the modifications required by a client to the assembly line 1,2 and 3 are listed and analysed to understand which could be the operations that must be performed to restore a line after usage.

The client made a request to Cosberg because they needed an assembly line for a new family of hinges. Therefore, Cosberg proposed to reconfigure the previous mentioned line instead of building a brand new one.

The reconfiguration of the line is a clear example of circular economy in which the old product is recollected from the client, modified, and re-sent to the client for a new purpose.

This is a clear example of how a pay-per-use business model would work in the future.

In this paragraph it will be explained how the line will be reconfigured for the new hinges, this is important to understand which will be the process of recollection and reconfiguration.

First, all the changes needed will be listed, then an analysis on how to manage this process for effective implementation of pay-per-use in the future will be carried out.

### 5.4.1 Modifications

The modifications for the line are classified as:

- Mandatory modification, once the machine is recollected, this change is required by the machine builder to restore functionality.
- Possible modification, the client can decide if he wants to invest money to increase the efficiency and reliability of the machine by introducing new components or modules.

There are 4 main changes to update the whole line.

Possible modification:

1) The existing PLC (Siemens S7 300) will be changed with a new PLC (Siemens S7 1500). This change will also imply a change of the software linked to the PLC.
   This implies an increase of the TH of the machine from 5% to 8%.

Required modifications:

2) Line transportation: the profile guides will be updated to stainless steel guides, the pallets will have a anti-bouncing system, 2 inverter will be added to the return belt to control the speed.
3) The regulation system of the vibrating feeders will be moved out of the cabinet.
4) All the screwing mechanism will be changed to update them to newest version to avoid damaging the screws.

After the changes that will regard the whole line, the focus will be on the changes related to single station, the table below resumes all the modifications needed considering the classification between possible and required ones.

| | |
|---|---|
| P | POSSIBLE |
| M | MANDATORY |

| ASSEMBLY LINE 1 - Linear conveyor | | | |
|---|---|---|---|
| NAME | MODIFICATIONS | MODULES | CATEGORY |
| STATION 1A | New vibratory feeder with bigger diameter. Introduction of a cover on top and a button for start/stop. | 0_1 + 1_1 | M |
| STATION 1B | | 0_1 + 1_1 | |
| STATION 1D | | 0_1 + 1_2 + 17 | |
| STATION 1E | New possible electric riveting machine | 3 | P |
| STATION 1F | New brushless motor. | 11 | M |
| STATION 1G | New screwing driver module. | 1_1 + 17 | M |
| STATION 1H | New brushless motor. Addition of the tasks of station N. | 0_1 + 1_1 + 17 | M |
| STATION 1I | Brushless screw driver. | 0_1 + 7 | M |
| STATION 1L | | 5 | M |
| STATION 1M | New brushless motor. | 11 | M |
| STATION 1N | Dismantle the station, the vibratory feeding system will be moved to station H. | 0_1 + 1_2 | M |
| STATION 1P | Rebuild of the conveyor. Addition of autmatic waste eviction system. Possible introdcution of brushless motor. | 1_1 + 14 | M+P |

*Table 24: Line 1 modifications*

| ASSEMBLY LINE 2 - Rotary table | | | |
|---|---|---|---|
| NAME | MODIFICATIONS | MODULES | CATEGORY |
| STATION A1 | Adddition of a mechanical feeder. | 0_1 + 1_1 + 14 | M |
| STATION A4 | Improvements of the vibratory feedign system. | 0_1 + 2 | M |
| STATION A6 | | 14 | |
| STATION A8 | Addition of a door for manual addition of the component. | 1_1 | M |

*Table 25: Line 2 modifications*

| ASSEMBLY LINE 3 - Linear conveyor | | | |
|---|---|---|---|
| NAME | MODIFICATIONS | MODULES | CATEGORY |
| STATION 2A | | 17 + 1_1 | |
| STATION 2B | Fixture modification + brushless motor | 0_1 + 1_1 + 1_1 | M |
| STATION 2B | Fixture modification + brushless motor | 0_1 + 1_1 | |
| STATION 2C | | 3 | |
| STATION 2N | New brushless motor. | 0_1 + 1_1 + 17 | M |
| STATION 2D | New brushless motor. | 0_1 + 1_1 + 17 | M |
| STATION 2E | New brushless motor. | 14 | P |
| STATION 2H | New control system. | 14 | P |
| STATION 2L | 3 brushless motors. | 1_1 + 9 | M |
| STATION 2L | 3 brushless motors. | 1_1 + 9 | M |

*Table 26: Line 3 modifications*

## 5.5 Recollection and reconfiguration process analysis

The process of recollection and reconfiguration of a line is not only related to the product itself, but there are several factors that must be considered.

1) The recollected machine obviously takes space in the facility, therefore it must be considered that, to implement a pay-per-use BM, a dedicated space for recollection is required.
   This implies the need of additional spaces or the decrease of available spaces for building of new products.
   Cosberg has considered that, due to module disassembling and reassembling operations, the required space in the facility will be 20% higher respect to the process of creation of a new line.
2) The process of reconfiguration requires manpower, from the analysis of the real case it can be understood how much time is spent for reconfiguration. This time will be then compared to the time needed for the construction of the original line to understand the percentage of the time saved.
   It has been computed that the lead time to reconfigure a machine is approximately the 60% of the lead time needed to produce a new line. This implies that the lead time will be reduce by 40% and it can be considered as an important advantage respect to competitors.
3) By combining the materials recycled and the manhours saved it is possible to understand the cost saved by this process.
   The line considered in this work has been produced in 2013 and therefore the cost of reconfiguration, that affect the whole line, will be 80/90% of the cost of the initial line.
   This implies that after 8 years the cost of reconfiguration is still lower respect to the cost of building a brand-new line, therefore it can be easily understood that, by considering additional introduction of modularity and standardization of the components, in the future the cost of reconfiguration will be considerably lower.

All the information exploited can be extremely useful to understand the resources need for the future when there will be a complete shift toward a PPU business model.

## 5.6 Summary of identified key points

As explained in this chapter, PPU introduces different advantages that are now summarized:

1. Financial advantages: manufacturers can exploit the value of the product for many different lifecycles, this implies that the revenues that a single line can produce is higher respect to conventional BM in which the product is just sold to the client. Moreover, additional streams of revenues can be introduced for reconfiguration of upgrade of the system if required by the client. This will lead in a much tighter bond between the producer and the customer. As a drawback, the implementation of this BM requires the involvement of investors like banks to deal with the upfront investment that the machine builder must face.
   This BM also implies financial advantages for the customer that does not require to buy the machine with an upfront investment. This can be extremely important for customers that doesn’t have enough liquidity to afford to buy the product.

2. Technical advantages: the introduction of standard modules reduces the complexity of the product, and, thanks to the monitoring of the system and recollection of the product, continuous improvements actions can be identified to further improve the architecture of the machine. This will lead to reduction of costs required for product development, reduction of diversification of components, increase availability and quality of the product.

3. Operational advantages: the introduction of a modular architecture reduces the time to market required to deliver the product to customers that can be reduced up to 50%.
   Linked to that, also the time to market to reconfigure the product can be reduced up to 50%.

# Chapter 6 – Conclusions and future improvements

This work has addressed the main aspects that must be considered to properly implement a pay-per-use business model in manufacturing, with a focus on the design and the configuration of assembly lines.

Circular economy is becoming a very important scenario that is rising in different industries and it implies the reuse of products after a defined lifecycle is concluded.
Pay-per-use is a new business model that considers the paradigm of circular economy and the concept of servitization.

In a PPU business model the client does not buy the product, instead he buys the service related to the product, like for example a production capacity. This is an extremely important advantage for the customer because it does not need to consider an initial investment to buy the product, in fact the client pays only the production capacity that is used. This is an advantage in case of production systems because the client is protected against stoppage or failures of the product.

Given that context, the product, after a period of service to the client, will return to the producer that will reconfigure or restore the functions of the product for a different purpose or for a different client.

The flow of information and materials have been reported in an IDEF in chapter 3 that explains the interactions between the different functions inside a company if PPU is established.

The interactions between sales, engineering, manufacturing, finance, and the client increase due to higher complexity of this BM respect to conventional BM.

Another aspect that must be considered to develop a successful PPU business model is related to the design of the product that must be completely modified respect to conventional product architecture.

In fact, the machine cannot be designed as a single entity because it will not be possible to reconfigure it for future utilizations. The most important concept is to consider a reconfigurable machine, and this can be achieved by introducing the concept of modularity.

A modular product is composed by different independent entities, the modules, that can perform a defined function; they can be combined in infinite ways to obtain the final product.

4 levels of modularity must be considered to properly achieve a modular reconfigurable machine:

- Hardware.
- Software.
- Electrical.
- Pneumatic.

Not only the design has to be considered but also the process of configuration must be evolved because this process will be consistently different respect to configuration of traditional assembly line.

The complete process to configure a modular assembly line has been explained and it has also been developed considering several real assembly lines produced by an Italian SME: Cosberg S.p.a.

Cosberg has estimated that the configuration process implemented with a modular structure will require 3 months respect to the 6 months needed to reconfigure a non-modular assembly system, that leads to a reduction of 50% of the lead time to deliver the product to the customer.

The analysis of the modules used in 7 different lines have highlighted that the most important modules that must be developed to start the implementation of a PPU business model are: feeding system and pick and place systems that constitute the 60% of the modules present in the analysed lines.

Moreover, the process of reconfiguration has been considered because it has a key role in a pay-per-use BM, because the machine will return to the producer that has to restore its functions.

To better understand the process of reconfiguration, the real assembly line before mentioned has been considered and analysed to understand which the necessary steps are to revamp a line.

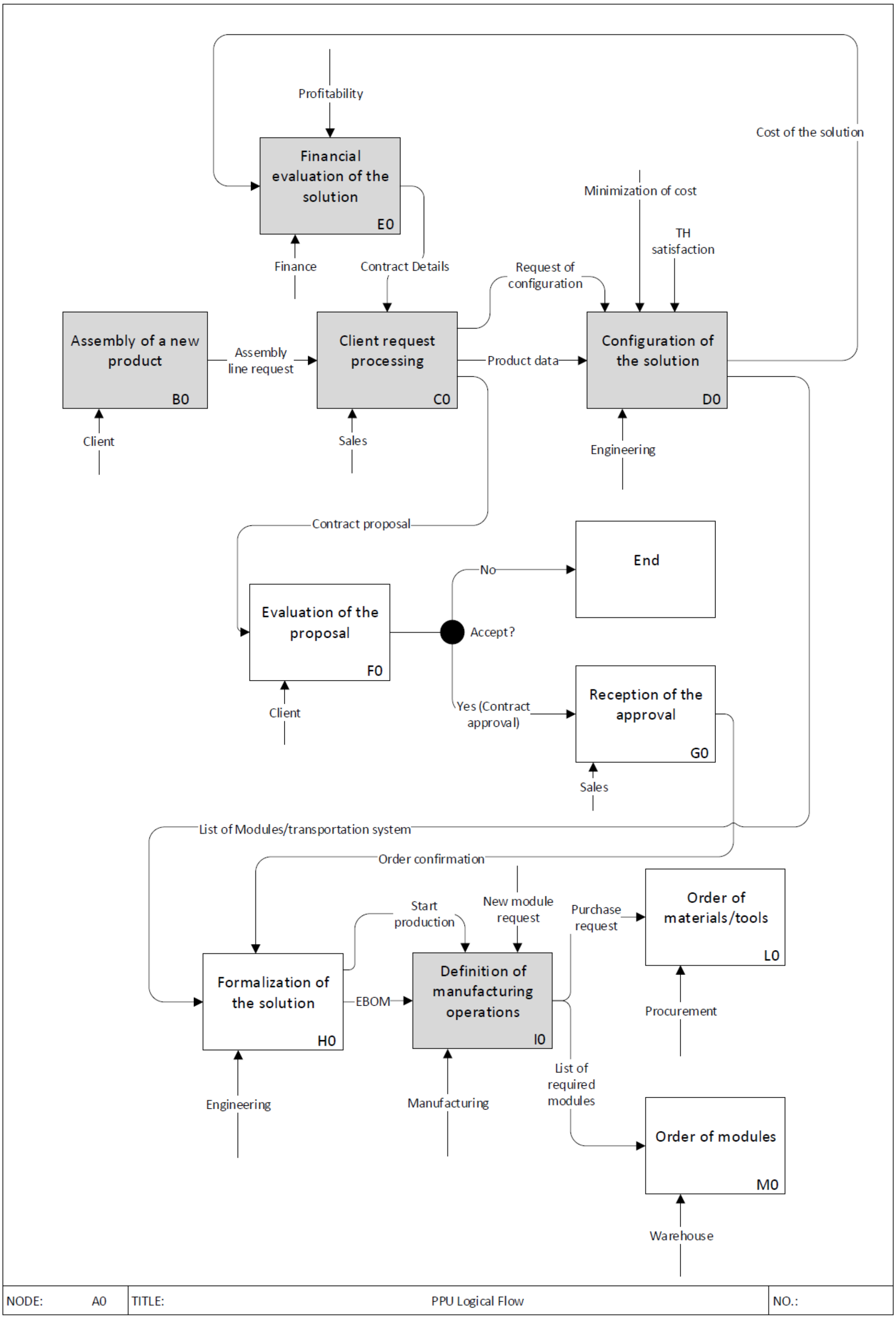
Cosberg has estimated that the reconfiguration process implemented with a modular structure will require 3/4 weeks respect to the 2 months needed to reconfigure a non-modular assembly system, that leads to a reduction of 50% of the lead time to deliver the product to the customer.

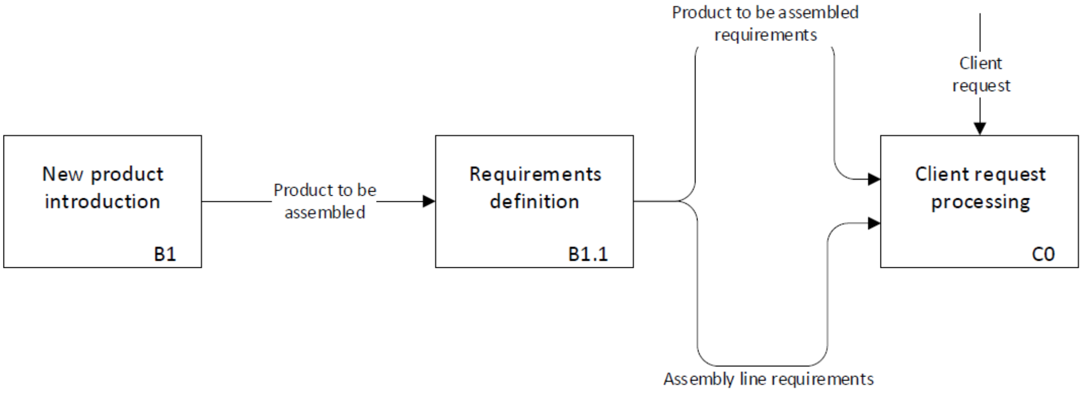
Further improvements can be found in the introduction of a digital twin for the assembly lines that, combined with the configurator, can represent a huge advantage for understanding the real time status of the line and for even easier configuration and reconfiguration process.
This step can be implemented by introducing 5G technology on the line that permits to send real time information to the server, and by the recreation of all the modules on CAM software.

Moreover, an additional step can be represented by the implementation of algorithms for preventive maintenance of the modules that can be seen an important advantage for the machine builder due to reduction of time to repair and reduction of time lost for production.

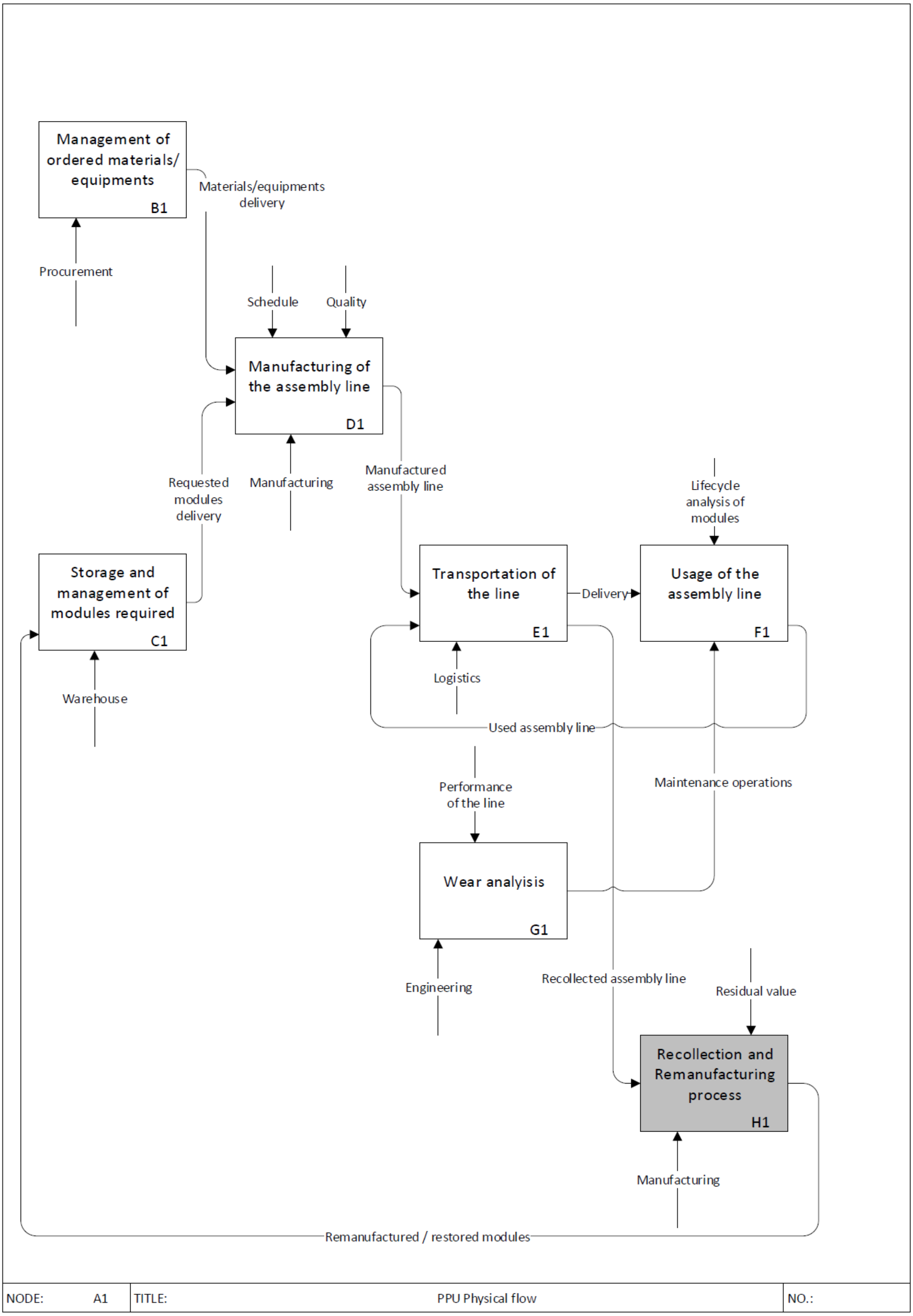
This is a key aspect because in a PPU business model the reduction of the time needed for failures and maintenance leads to an increase of the production rate that is linearly linked to the money earned by the machine builder.

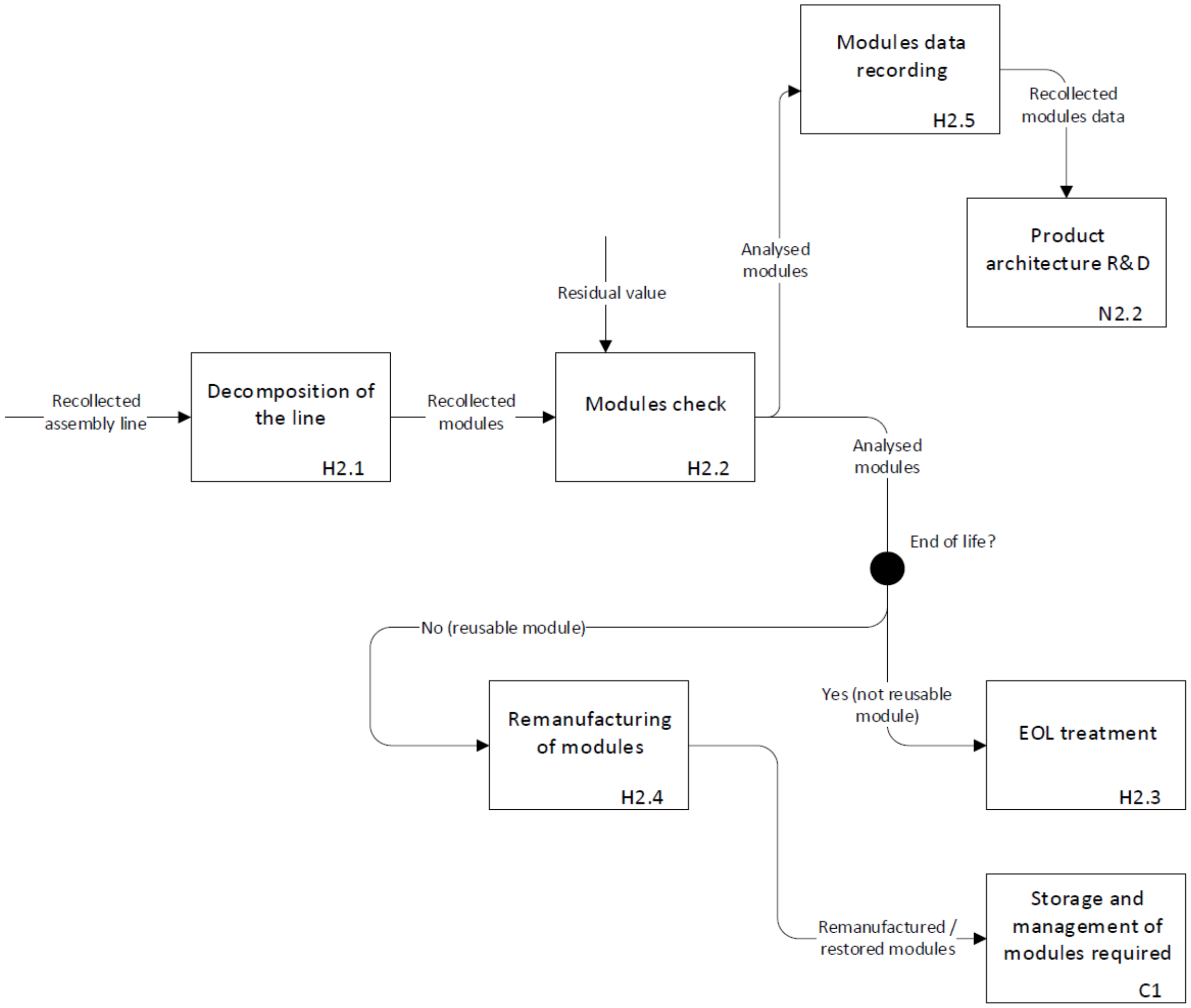
# Annex 1 – IDEF: Pay-per-Use





| | | | | |
|---|---|---|---|---|
| NODE: | B0 | TITLE: | Assembly of a new product | NO.: |


Management of ordered materials/ equipments
B1
Materials/equipments delivery
Procurement
Schedule
Quality
Manufacturing of the assembly line
D1
Requested modules delivery
Manufacturing
Manufactured assembly line
Lifecycle analysis of modules
Storage and management of modules required
C1
Transportation of the line
E1
Delivery
Usage of the assembly line
F1
Logistics
Warehouse
Used assembly line
Performance of the line
Maintenance operations
Wear analyisis
G1
Engineering
Recollected assembly line
Residual value
Recollection and Remanufacturing process
H1
Manufacturing
Remanufactured / restored modules
NODE: A1
TITLE: PPU Physical flow
NO.:



| | | | | |
|---|---|---|---|---|
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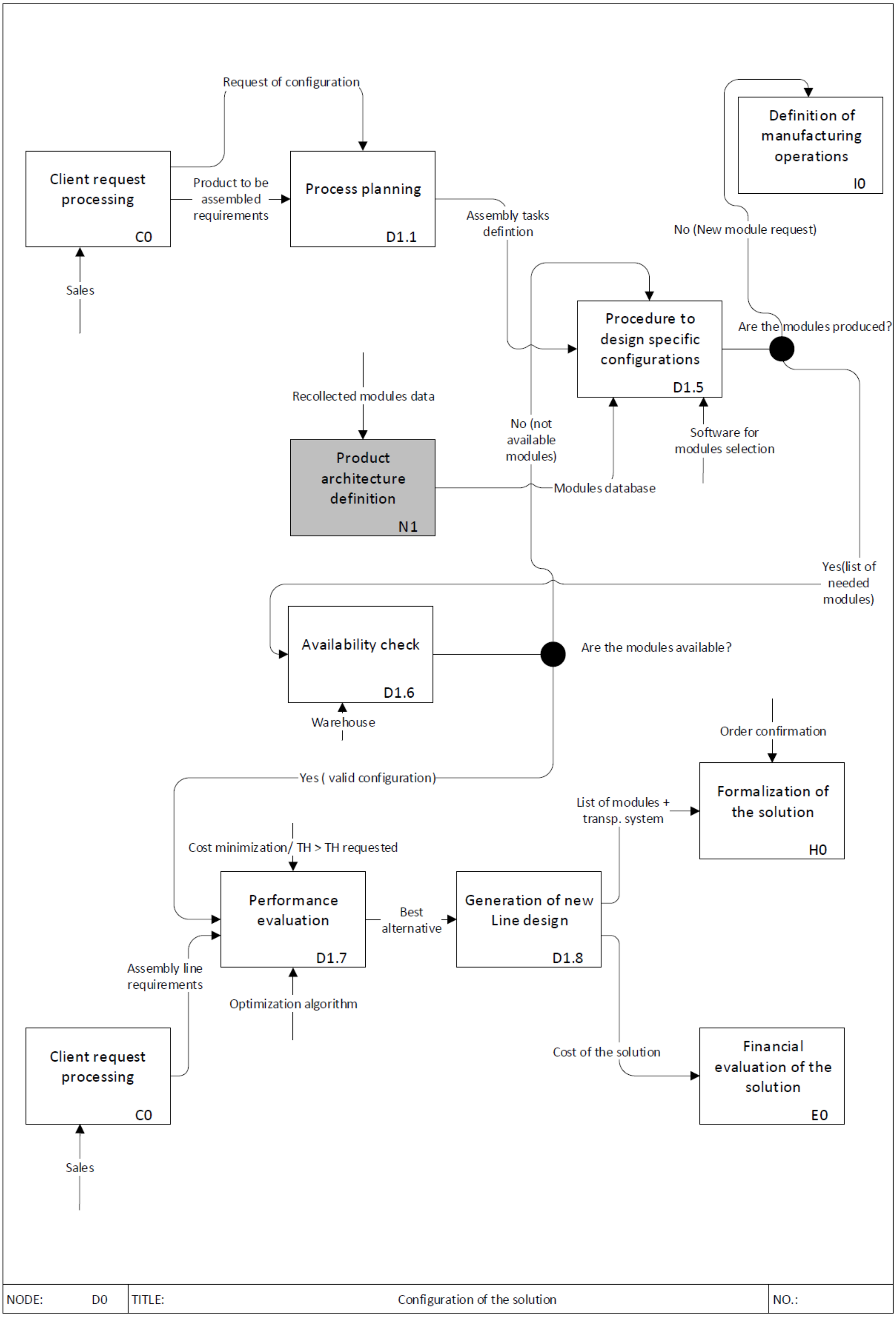
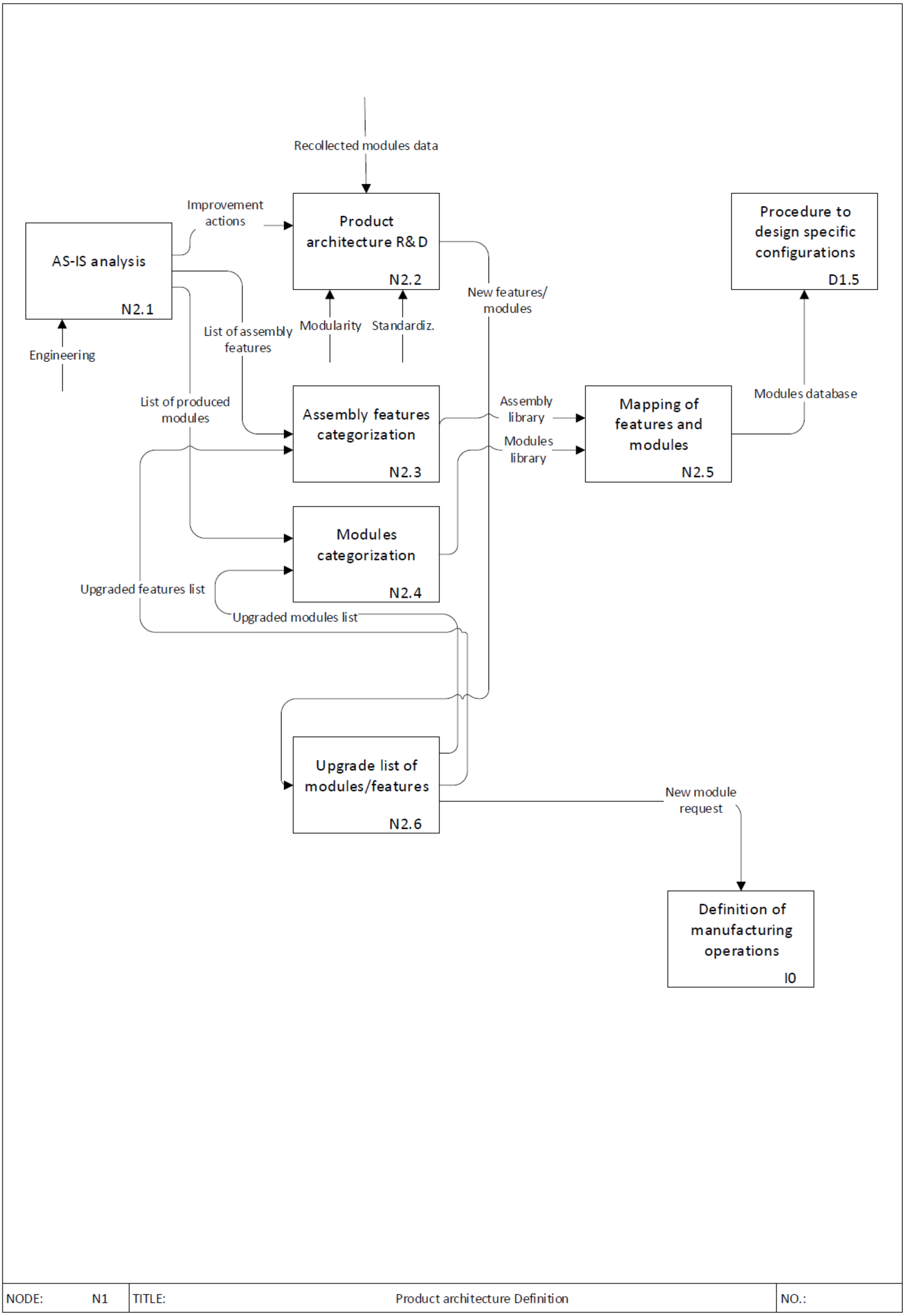
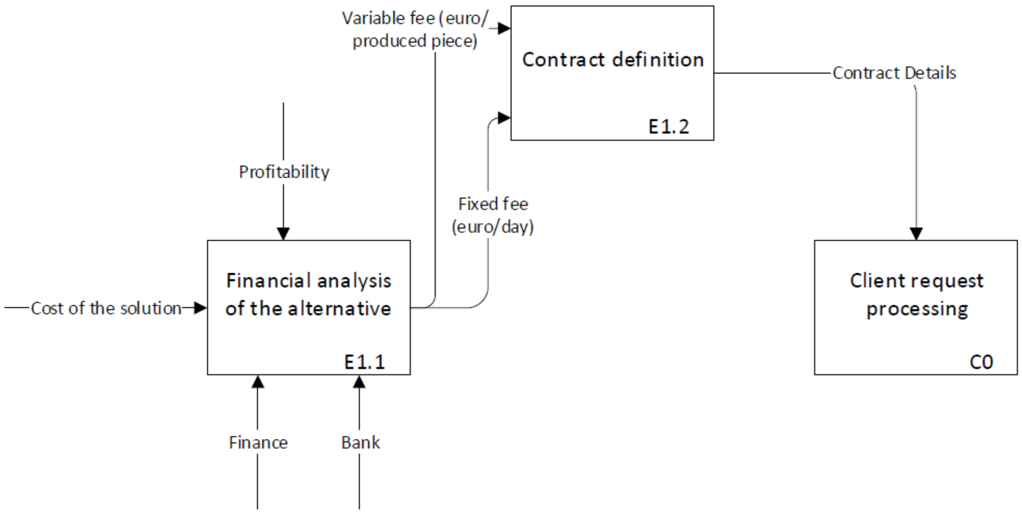

Request of configuration
Client request processing
C0
Product to be assembled requirements
Process planning
D1.1
Assembly tasks defintion
Definition of manufacturing operations
I0
No (New module request)
Sales
Procedure to design specific configurations
D1.5
Are the modules produced?
Recollected modules data
Product architecture definition
N1
No (not available modules)
Software for modules selection
Modules database
Yes(list of needed modules)
Availability check
D1.6
Are the modules available?
Warehouse
Order confirmation
Yes ( valid configuration)
Formalization of the solution
H0
List of modules + transp. system
Cost minimization/ TH > TH requested
Performance evaluation
D1.7
Best alternative
Generation of new Line design
D1.8
Assembly line requirements
Optimization algorithm
Cost of the solution
Client request processing
C0
Financial evaluation of the solution
E0
Sales
NODE: D0
TITLE: Configuration of the solution
NO.:


Recollected modules data
Improvement actions
Product architecture R&D
N2.2
AS-IS analysis
N2.1
Engineering
List of assembly features
Modularity
Standardiz.
New features/ modules
Procedure to design specific configurations
D1.5
List of produced modules
Assembly features categorization
N2.3
Assembly library
Modules library
Mapping of features and modules
N2.5
Modules database
Modules categorization
N2.4
Upgraded features list
Upgraded modules list
Upgrade list of modules/features
N2.6
New module request
Definition of manufacturing operations
I0
NODE:
N1
TITLE:
Product architecture Definition
NO.:



| | | | | |
|---|---|---|---|---|
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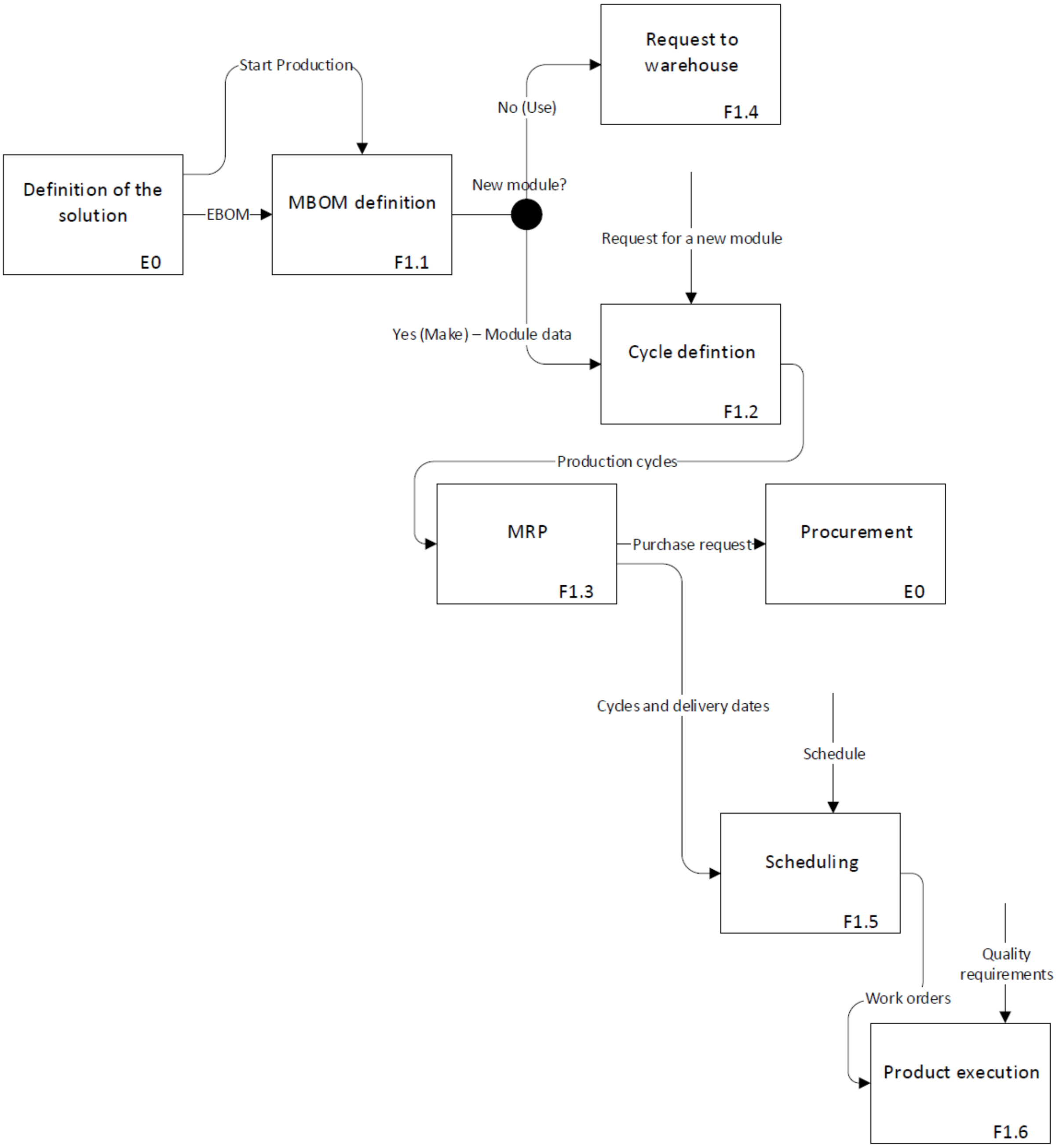

| | | | | | |
|---|---|---|---|---|---|
| NODE: | F0 | TITLE: | Definition of manufacturing operations | NO.: | |

# Annex 2 - Module selection algorithm

```
clear all
clc

% Inputs from the client (constraints)
lung_max = 30; %maximum available space(meter)
thmin = 2400/3600; %pieces/second
dmaxcomp = 0.01; %maximum dimension of the components(meter)

% Output from the process planning (list of required tasks in the right
% order)
process_planning1 = ["pickplace2Darm", "lubrication","tapping","lubrication", "screwing",
"presenceinspection",
"bending","lubrication","pickplace2Darm","pickplace2Darm","riveting", "pickplace2Darm",
"calibration", "pickplace2Darm" ]; %definitions of task needed
n_ops1 = size(process_planning1,2); %number of operations required
feeding = "Vibratory feeder";

% STEP 1: Identification of the type of conveyor and feeding system
typeoftransp = [];
if dmaxcomp > 0.02
    typeoftransp = "Linearconv";
    feeding = "Manual feeding";
elseif n_ops1 > 14
    typeoftransp = "Linearconv";
else
    typeoftransp = "Rotary table";
end

%STEP 2: identification of functions needed
f = []; %required functions for the assembly line

% LIST OF FUNCTIONS: definition of the functions and their relative attributes
for i = 1: n_ops1
   if process_planning1(i) == "pickplace2Darm"
       f(i)=1;
   elseif process_planning1(i) == "pickplace2Dcam"
       f(i)=1.2;
   elseif process_planning1(i) == "pickplace3D"
       f(i)=2;
   elseif process_planning1(i) == "screwing"
       f(i)=3;
   elseif process_planning1(i) == "riveting"
       f(i)=4;
   elseif process_planning1(i) == "welding"
       f(i)=5;
   elseif process_planning1(i) == "soldering"
       f(i)=6;
   elseif process_planning1(i) == "shrinking"
       f(i)=7;
   elseif process_planning1(i) == "gluing"
       f(i)=8;
   elseif process_planning1(i) == "clinching"
       f(i)=9;
   elseif process_planning1(i) == "bending"
       f(i)=10;
   elseif process_planning1(i) == "tapping"
       f(i)=11;
   elseif process_planning1(i) == "functionalinspection1"
       f(i)=12;
  elseif process_planning1(i) == "functionalinspection2"
       f(i)=13;
  elseif process_planning1(i) == "functionalinspection3"
       f(i)=14;
  elseif process_planning1(i) == "press"
```

```
       f(i)=15;
  elseif process_planning1(i) == "disentangleforsprings"
       f(i)=16;
  elseif process_planning1(i) == "presenceinspection"
       f(i)=17;
  elseif process_planning1(i) == "dimensioninspection"
       f(i)=18;
  elseif process_planning1(i) == "visionsystem"
       f(i)=19;
  elseif process_planning1(i) == "lubrication"
       f(i)=20;
  elseif process_planning1(i) == "calibration"
       f(i)=21;
   end
end

%Parameters of the modules
%Production rates
mu1_1 = 0.97 ;
mu1_2 = 1.39 ;
mu1_3 =0.55;
mu2 = 1;
mu3 = 1;
mu4 = 1;
mu5 = 1;
mu6 = 1;
mu7 = 1;
mu8 = 1;
mu9 = 1;
mu10 = 1;
mu11_1 = 1.33 ;
mu11_2 = 0.667 ;
mu11_3 =0.333;
mu12=1;
mu13= 1;
mu14=1;
mu15=1;
mu16=1;
mu17=10;
mu18=10;

%STEP 3: Creation of the struct for each module
%Function type1: pick and place
module1_1 = struct('mu', [mu1_1; 0],'name', "module1_1", 'Function', 1, 'length', 1);
%arm (2D)
module1_2 = struct('mu', [mu1_2; 0], 'name', "module1_2", 'Function', 1.2, 'length',
0.5); %cam(2D)
module1_3 = struct('mu', [mu1_3; 0],'name', "module1_3", 'Function', 2, 'length', 1.5);
%robot (3D)

%Function type2: : Joining
module2 = struct('mu', [mu2; 0],'name',"module2", 'Function', 3, 'length', [1]);
%screwing
module3 = struct('mu', [mu3; 0],'name',"module3", 'Function', 4, 'length', [1]);
%riveting
module4 = struct('mu', [mu4; 0],'name',"module4", 'Function', 5, 'length', [1]); %welding
module5 = struct('mu', [mu5; 0],'name',"module5", 'Function', 6, 'length', [1]);
%soldering
module6 = struct('mu', [mu6; 0],'name',"module6", 'Function', 7, 'length', [1]);
%shrinking
module7 = struct('mu', [mu7; 0],'name',"module7", 'Function', 8, 'length', [1]); %gluing
module8 = struct('mu', [mu8; 0],'name',"module8", 'Function', 9, 'length', [1]);
%Clinching

%function type3: Plastic deformation
module9 = struct('mu', [mu9; 0],'name',"module9", 'Function', 10, 'length', [2]);
%Bending

%function type4: Material removal (tapping)
```

```
module10 = struct('mu', [mu10; 0], 'name',"module10", 'Function', 11, 'length', [1]);
%Tapping

%function type5: functional inspection
module11_1 = struct('mu', [mu11_1; 0],'name',"module11_1", 'Function', 12, 'length',
[1]); %Linear actuation 100N
module11_2 = struct('mu', [mu11_2; 0],'name',"module11_2", 'Function', 13, 'length',
[1]); %Linear actuation 200N
module11_3 = struct('mu', [mu11_3; 0],'name',"module11_3", 'Function', 14, 'length',
[1]); %Linear actuation 500N

%function type6: disentangle and feeder for springs
module12 = struct('mu', [mu12; 0],'name',"module12", 'Function', 15, 'length', [0.2]);

%function type7: press
module13 = struct('mu', [mu13; 0],'name',"module13", 'Function', 16, 'length', [1]);

%function type8: presence inspection
module14 = struct('mu', [mu14; 0],'name',"module14", 'Function', 17, 'length', [1]);

%function type9: dimension inspection
module15 = struct('mu', [mu15; 0],'name',"module15", 'Function', 18, 'length', [1]);

%function type10: vision system
module16 = struct('mu', [mu16; 0],'name',"module16", 'Function', 19, 'length', [1]);

%function type11: lubrication system
module17 = struct('mu', [mu17; 0],'name',"module17", 'Function', 20, 'length', [1]);

%function type12: calibration system
module18 = struct('mu', [mu18; 0],'name',"module18", 'Function', 21, 'length', [1]);


%STEP 4: Line composition (modules selection)
for k = 1: n_ops1
    if module1_1.Function == f(k)
    stat(k) = module1_1;
    elseif module1_2.Function == f(k)
    stat(k) = module1_2;
    elseif module1_3.Function == f(k)
    stat(k) = module1_3;
    elseif module2.Function == f(k)
    stat(k) = module2;
    elseif module3.Function == f(k)
    stat(k) = module3;
    elseif module4.Function == f(k)
    stat(k) = module4;
    elseif module5.Function == f(k)
    stat(k) = module5;
    elseif module6.Function == f(k)
    stat(k) = module6;
    elseif module7.Function == f(k)
    stat(k) = module7;
    elseif module8.Function == f(k)
    stat(k) = module8;
     elseif module9.Function == f(k)
    stat(k) = module9;
    elseif module10.Function == f(k)
    stat(k) = module10;
    elseif module11_1.Function == f(k)
    stat(k) = module11_1;
    elseif module11_2.Function == f(k)
    stat(k) = module11_2;
    elseif module11_3.Function == f(k)
    stat(k) = module11_3;
    elseif module12.Function == f(k)
    stat(k) = module12;
    elseif module13.Function == f(k)
    stat(k) = module13;
    elseif module14.Function == f(k)
```

```
    stat(k) = module14;
    elseif module15.Function == f(k)
    stat(k) = module15;
    elseif module16.Function == f(k)
    stat(k) = module16;
    elseif module17.Function == f(k)
    stat(k) = module17;
    elseif module18.Function == f(k)
    stat(k) = module18;
    end
end


%CHECK: length of the line must be lower than maximum available length
sum1 = [];
th_stat = [];
n_mod_stat = ones(1, n_ops1);


for i = 1:n_ops1
    sum1(i) = stat(i).length;
end
total = sum(sum1);


if total > lung_max && typeoftransp == "Linearconv"
    stat(1).name = "invalid";
elseif  typeoftransp == "Linearconv"
%CHECK: duplication of modules to satisfy the minimum TH
for i = 1:n_ops1
    th_stat(i) = stat(i).mu(1,1);
    while th_stat(i) < thmin
        n_mod_stat(i) = n_mod_stat(i)+1;
        th_stat(i) = th_stat(i)+ stat(i).mu(1,1);
    end
end
end

%CHECK: rotary table TH satisfaction
if typeoftransp == "Rotary table"
for i = 1:n_ops1
    th_stat(i) = stat(i).mu(1,1);

    if th_stat(i) < thmin
        typeoftransp = "Linearconv";
    while th_stat(i) < thmin
        n_mod_stat(i) = n_mod_stat(i)+1;
        th_stat(i) = th_stat(i)+ stat(i).mu(1,1);
    end
    end
end
end


%STEP 5:
%Final result: 1)Type of transportation system
%2)Type of feeding system
%3)Type of module and quantity (non valid configurations
%have name equal to invalid)

disp(typeoftransp)
disp(feeding)
disp(int2str(n_ops1))
disp("Alternative 1")
if stat(1).name == "invalid"
    disp("Non valid configuration")
else disp([stat.name])
    disp(n_mod_stat)
end
```

# Chapter 7 – Bibliography

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