Politecnico di Torino

Department of Mechanical and Aerospace Engineering

Master’s Degree in Automotive Engineering

Manufacturing and cost analysis of cylinder head, turbocharger, basement and crankshaft for a high-power density internal combustion engine used as range extender

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Alla mia mamma e il mio papà sempre magnificamente presenti,

a mio fratello, migliore guida in questo viaggio di vita,

a Valentina la mia splendida e dolce metà,

ai miei amici di sempre fantastici compagni in questa splendida avventura.

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Abstract

The thesis work has been developed in collaboration with the company "Leonardo Engineers for integration S.R.L.", it is part of an innovative and totally brand-new hybrid electric powertrain design.

The project is included in a series of works previously carried out by other students, in collaboration with the company, aimed to design and optimize the internal combustion engine that will be exploited as a range extender unit for the series hybrid electric vehicle.

General design goal is the minimization of fuel consumption without penalizing the engine power output; other two important aspects that lead the project are the cost involved in the internal combustion engine manufacturing and the noise and vibration produced.

In this work the cost analysis and the feasibility of the project will be started and some components such as the engine basement, the cylinder head, the crankshaft and the turbocharger assembly will be further investigated.

Some tools and applications have been used to pursue the targets: the CAD drawings of the engine, part of previously projects, made with PTC Creo Parametric, have been analysed and studied with Solidworks; instead, for the calculation and for the Engineering bill of material, Microsoft Excel sheets have been widely exploited.

1. Introduction

In the last few decades, the growing need of cleaner and more sustainable solution has influenced all manufacturing sectors: automotive OEMs have not been exempted from this situation.

OEMs' answer has been the introduction and design of new powertrains and technologies capable of reducing fuel consumption and, consequently, the pollutant produced by the traditional internal combustion engine. Moreover, other energy sources have been investigated in order to further lowering the emissions, in particular, electric machine have been quickly widespread and the cooperation between internal combustion engine and electric motor – i.e. hybrid electric architecture - has been the solution and appears to be the smarter response for the near future environmental welfare.

The background described above has induced the Company's president - Ing. Pietro Bianchi - to study and propose an innovative solution that has also became the start of the collaboration between Politecnico di Torino and his Company.

The project has now reached an advanced point since it was started in 2016, all the main components of the internal combustion engine and electric machine has been designed: data and CAD drawings are available. Therefore, the work described here has been focused on the feasibility of the project, the forecast costs and working procedure evaluation.

The thesis has subdivided following a logical procedure: in the first chapter – 1. Introduction – the historical background and a small description of what will be found in the thesis is described; then, in the second chapter – 2. Hybrid Electric Vehicle – the architecture and the main features of the engine electrification processes are described. The third chapter – 3. Internal Combustion Engine – aims of presenting and introducing internal combustion engine operation and in which way the fuel consumption affects engine management and design choices. Chapter four – 4. Engine Layout and Management – is dedicated to the engine layout under investigation description and all its peculiarities are pointed out. In the fifth chapter – 5. Cost Analysis – the core of the work is proposed, the procedures followed are reported and some theory outline is present too. In the sixth chapter – 6. Results – the analytical data obtained will be reported in an organized way to present the work outcomes. The seventh chapter – 7. Conclusions – reports a brief overview of the work, pointing out strength and weak points of the project under cost and feasibility perspective.

1.1 Historical Background

The decade started with 2020 has been marked as the period that shall know the transition to a more sustainable world. The need of green and cleaner solutions, in all the processes that characterize the human existence, is mainly due to the worrying changes that the Earth are showing, above all, the dramatic quick rises of temperature. This overall warmer climate brings with it innumerable drawbacks such as the desertification.

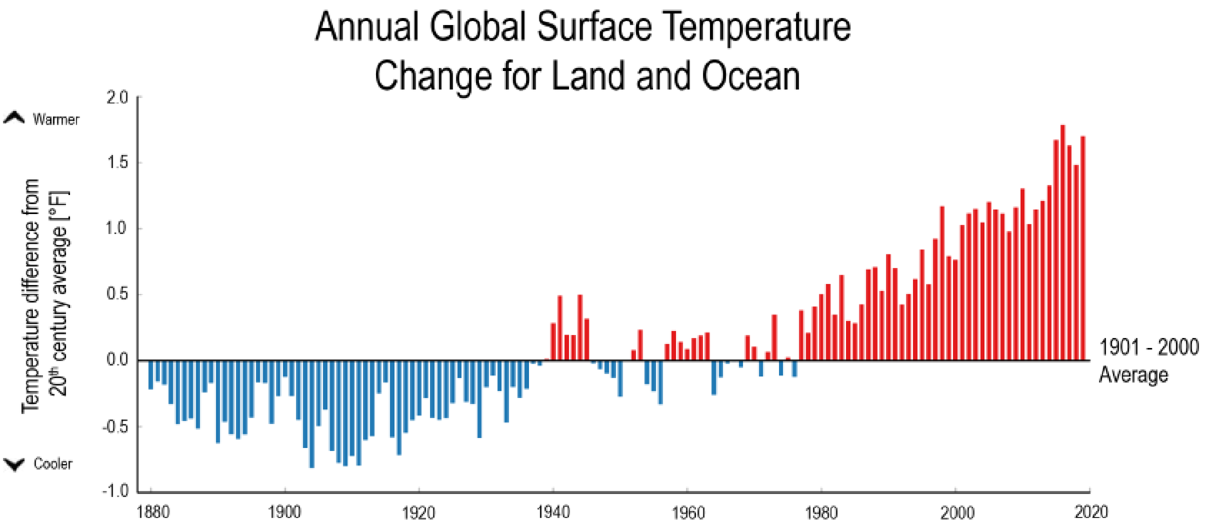


FIGURE 1. INCREASE IN TEMPERATURE OVER LAST DECADES
SOURCE: HTTPS://WWW.QUALENERGIA.IT/ARTICOLI/CLIMA-2020-CHIUDE-IL-DECENNIO-PIU-CALDO-DI-SEMPRE/

A gain of around two degrees has been experienced in the last year, one of the most important cause is the growing massive presence of greenhouse gases in the Earth's atmosphere. These agents are a result of the anthropogenic activities; a huge amount of evidences prove that, in particular, the linear increases of temperature starting after industrial revolution and the same gain of the concentration of those gases in the atmosphere is the main proof. [1][2]

The greenhouse gases are substances present in ambience in trace concentration capable of capturing the reflected energy from the Earth surface. Basically, they are transparent for the high frequencies of solar wave radiation but opaque for the infrared wave reflected by the Earth, under practical point of view they act as one way filter, allowing the passage of energy coming from the sun blocking at the same time the radiations reflected by the Earth.

Carbon dioxide (CO_2) is a natural component of Earth's ambience, nevertheless, it is also one of the combustion reaction products. The ideal combustion reaction of a liquid fuel C_aH_b can be described through the chemical balance reported here (1):

$$C_aH_b + \left(a + {}^{b}/_{4}\right)(O_2 + 3.773N_2) = aCO_2 + {}^{b}/_{2}\, H_2O + 3.773\left(a + {}^{b}/_{4}\right)N_2 \quad (1)$$

This aspect and its great greenhouse peculiarities makes the carbon dioxide one of the most responsible of the average temperature gain and so the worst enemies against climate change battle. Automatically, being CO_2 the result of the combustion process, the internal combustion engine, that equips still the majority of vehicle, must be carefully designed to maximize the reduction in fuel consumption and so in carbon dioxide production. [3]

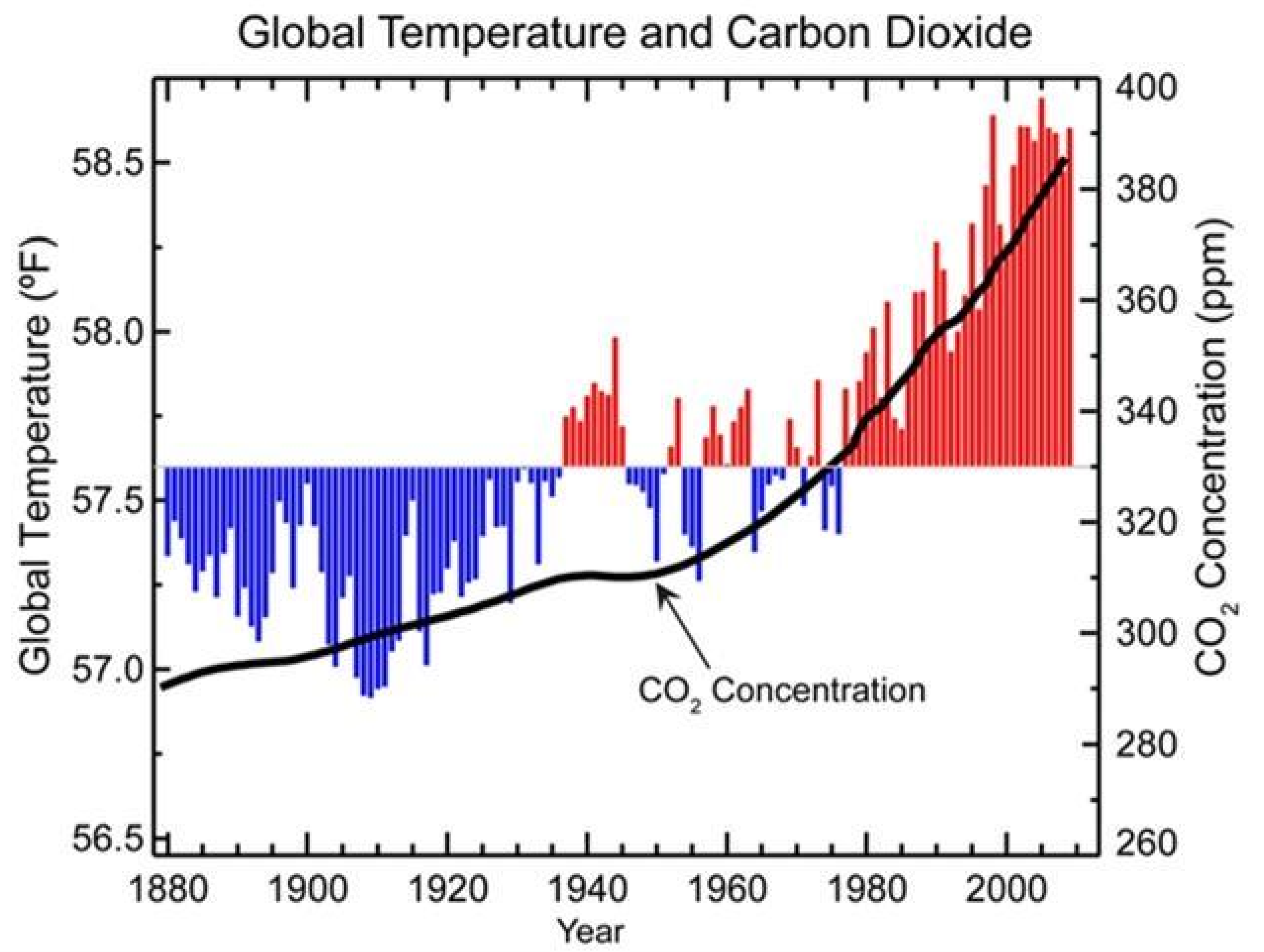


FIGURE 2. RELATION BETWEEN CO_2 CONCENTRATION AND TEMPERATURE INCREASES
SOURCE: HTTPS://WWW.RETECLIMA.IT/IL-CAMBIAMENTO-CLIMATICO/

Up to now the ideal chemical combustion reaction is considered, however, the actual chemical process, occurring in internal combustion engine, leads also to the production of some pollutant. These harmful engine emissions are mainly represented by incomplete combustion reaction products like carbon monoxide (CO) and unburnt hydrocarbon (HC); moreover, an incorrect presence of oxygen – when the mixture is lean - inside the combustion chamber coupled with high temperature could give rise to the production of nitrogenous compound (NO_x) that are other injurious elements.

These substances are the most important pollutants produced by combustion engine, nevertheless, some other matters can be observed at the engine outlet, other examples are the particulate (PM) produced mainly by diesel engine and gasoline direct injection engine, the sulfur dioxide and formaldehyde.

They can be categorized as primary and secondary pollutants, the formers are those directly produced by human activity (e.g. carbon monoxide, NO_x), the latter, instead, are the ones generated from primary pollutants that react with sunlight or component present in ambience (e.g. sulfuric acid). Below is reported a table that summarize the most important harmful elements and their consequences on human and environmental beings, attributable to internal combustion engine processes:

Emission Component	Atmospheric Reaction Products	Biological Impact
Gas Phase		
Carbon monoxide	-	Highly toxic to humans; blocks oxygen uptake.
Nitrogen oxides	Nitric acid, ozone	Nitrogen dioxide is a respiratory tract irritant and major ozone precursor. Nitric acid contributes to acid rain.
Sulfur dioxide	Sulfuric acid	Respiratory tract irritation. Contributor to acid rain.
Carbon dioxide	-	Major contributor to global warming.
Saturated hydrocarbons (Alkanes, < C_{19})	Aldehydes, alkyl nitrates, ketones	Respiratory tract irritation. Reaction products are ozone precursors (in the presence of NO_x).
Unsaturated hydrocarbons (Alkenes < C_5)	Aldehydes, ketones	Respiratory tract irritation. Some alkenes are mutagenic and carcinogenic. Reaction products are ozone precursors (in the presence of NO_x).
Formaldehyde	Carbon monoxide, hydroperoxyl radicals	Formaldehyde is a probable human carcinogen and an ozone precursor (in the presence of NO_x).
Higher aldehydes (e.g., acrolein)	Peroxyacyl nitrates	Respiratory tract and eye irritation; causes plant damage.
Monocyclic aromatic compounds (e.g. benzene, toluene)	Hydroxylated and hydroxylated-nitro derivatives	Benzene is toxic and carcinogenic in humans. Some reaction products are mutagenic in bacteria (Ames assay).
PAHs (< 5 rings) (e.g. phenanthrene, fluoroanthene)	Nitro-PAHs (<5 rings)	Some of these PAHs and nitro-PAHs are known mutagens and carcinogens.
Nitro-PAHs (2 and 3 rings) (e.g. nitronaphtalenes)	Quinones and hydroxylated-nitro derivatives	Some reaction products are mutagenic in bacteria (Ames assay).

TABLE 1. POLLUTANTS AND THEIR CONSEQUENCES SOURCE: ENGINE EMISSIONS CONTROL
SOURCE: "ENGINE EMISSIONS CONTROL-01. INTRODUCTION_EMISSIONS-2020" (PROF. MILLO FEDERICO)

To control and reduce as much as possible the harmful substances described above, in the last years, aftertreatment systems have helped the environmental cause, different strategies have been developed for spark ignition engine and for compression ignition engine. Three-way catalytic converters have been widely employed on gasoline engine, while lean NO_x trap or selective catalytic converter, coupled with diesel particulate filter, have served the diesel powertrain.

Those systems coupled with more and more stringent regulations have produced significant but not at all satisfactory results. Furthermore, aftertreatment systems, since carbon dioxide as it has been said before is a natural compound not considered as harmful, are not designed to also reduce the presence of CO_2 resulting in practically zero influence on its production. The only countermeasures usable in that battle is the fuel consumption reduction, acts on design parameters is the most widespread strategy: downsizing and turbocharger adoption – i.e. the reduction of engine displacement coupled with the exploitation of better efficiencies and performances guaranteed by turbocharger- , better aerodynamic architectures, exhaust recirculation gases, weight reduction and a smart engine control system are the main solutions adopted nowadays. However, a certain limit cannot be overcame and, consequently, the regulations forecast for the next year cannot be achieved. [3]

Below it is reported a graph that shows the results of different strategies against fuel reduction with respect to the cost involved in development. It can be noticed, as it has been underlined above, that from a certain point no more benefits can be obtained. Then it is proposed the target imposed by regulations in the next years and the improvement in CO_2 production in the last periods.

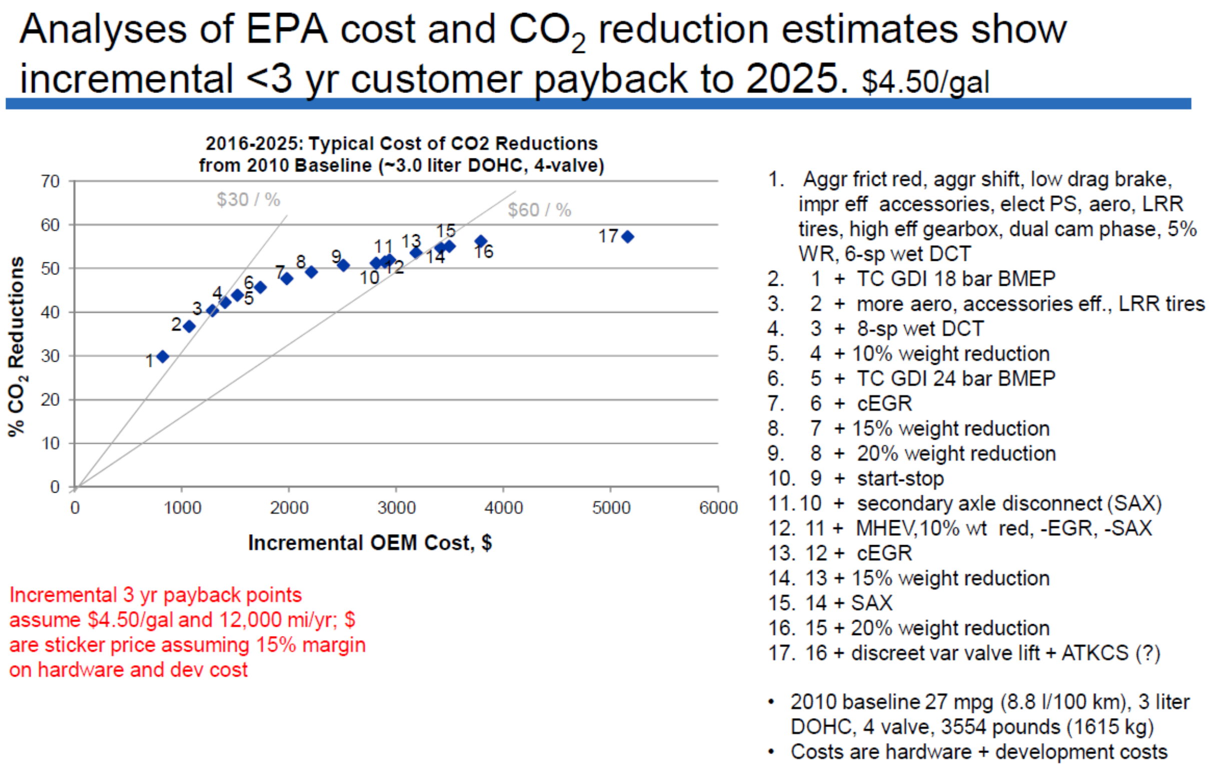


Figure 3. Fuel reduction strategies and related cost

Source: Millo F., "Engine emissions control- 05. Gasoline-Future-Develop"

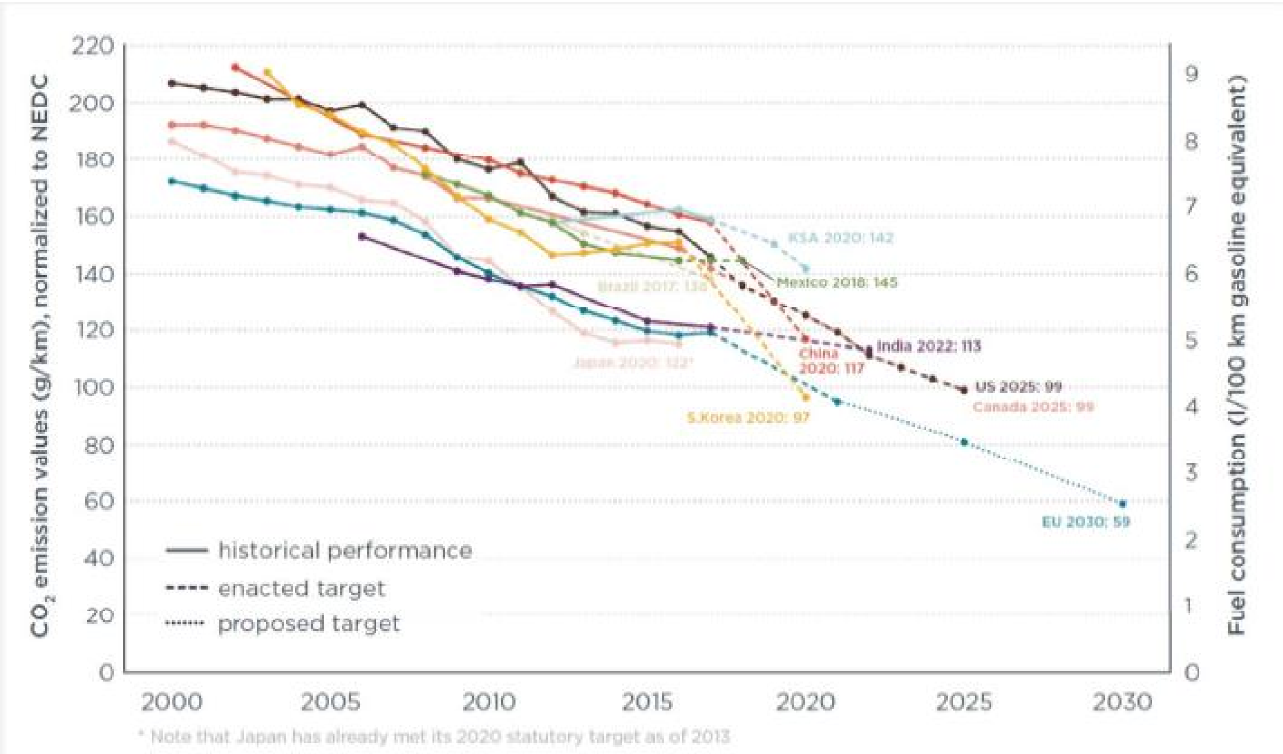


Figure 4. CO_2 emissions regulation limit

Source: Spessa E., "Design of engine and control system- L01. TechRM4RV", Torino 2020

Having understood the bad environmental situation and the more and more severe restriction imposed to produce ICE (i.e. Internal Combustion Engine), car manufacturers, in the last year, have explored new sources of energy and architecture for the future powertrain. Electric energy has been one of the most appreciated and studied solution, in particular, some peculiarities of electric motor have not gone unnoticed.

Electric machines have many important advantages with respect to the classical combustion engine, indeed, high efficiency in the range between 80% and 90% can be obtained, a far greater value compared with the peak of 40% guaranteed by a very well-designed ICE. Another important aspect is the better quality and regulation of motor torque, they appear to be suited for the transportation application as could be seen in a torque versus speed graph; a constant maximum torque is experienced for low-speed values, then, increasing the engine speed, torque outcome is reduced gradually. [6]

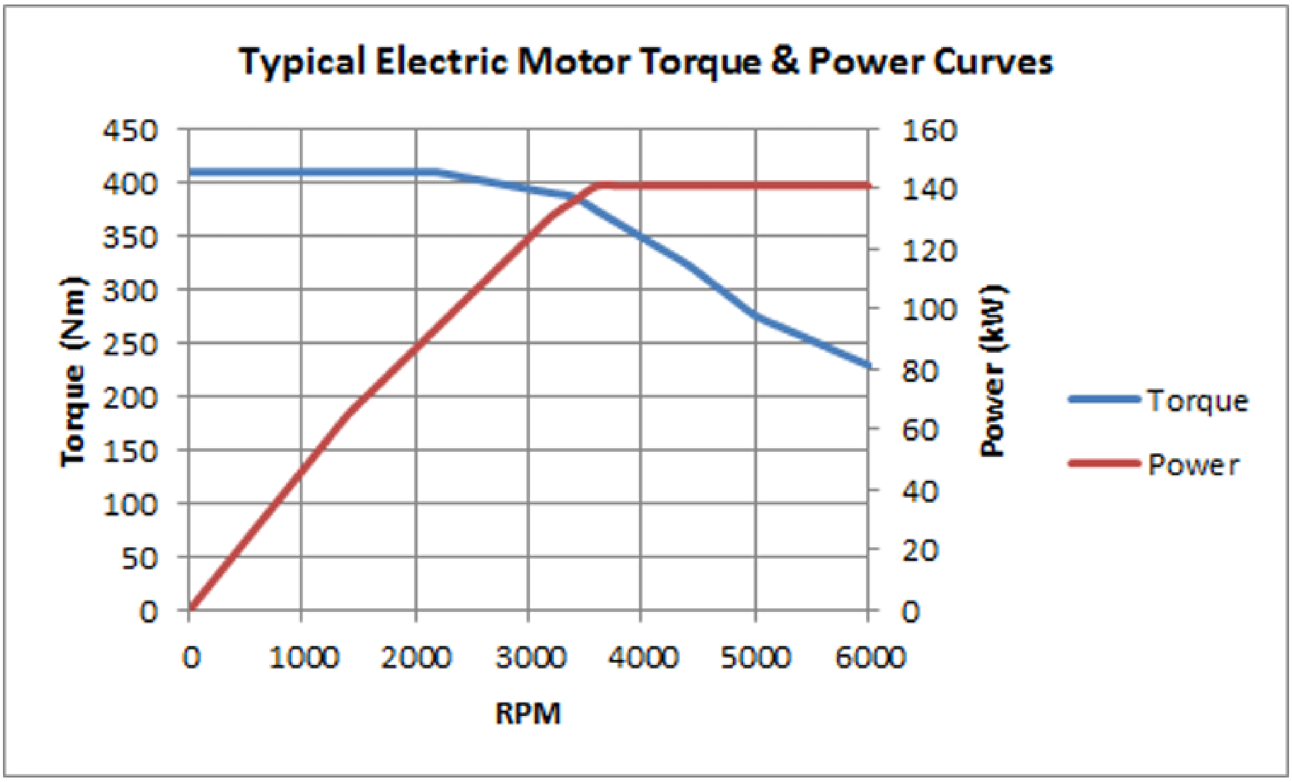


FIGURE 5. TYPICAL TORQUE (AND POWER) VS SPEED FOR ELECTRIC MOTOR
SOURCE: "HTTPS://THECONVERSATION.COM/HERES-WHY-ELECTRIC-CARS-HAVE-PLENTY-OF-GRUNT-OOMPH-AND-TORQUE-115356"

Last, the most important benefit is that, with electric propulsion, noxious and carbon dioxide direct emission is nullified; this aspect has addressed OEM to investigate and follow the electric way.

Nevertheless, some negative points must be carefully considered, energy storage is the most important and difficult one. The technology offered by the most performant batteries nowadays is not enough and even not comparable with the range guaranteed by fossil fuel. To be clearer, the specific power and energy stored in a battery are, respectively, 1 kW/kg and 130 Wh/kg, very small value if compared with the 12 kWh/kg specific energy provided by gasoline. [7]

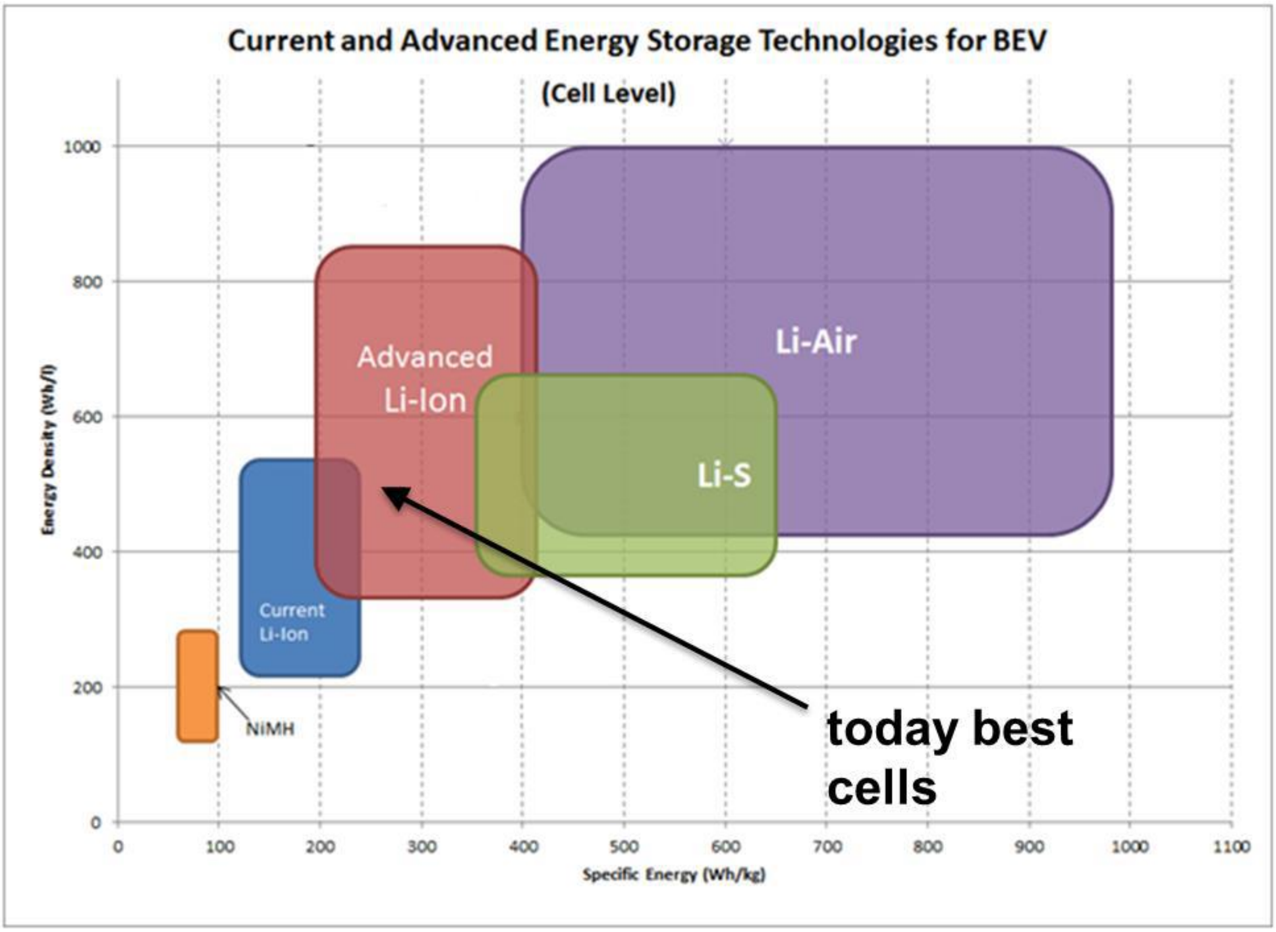


FIGURE 6. BATTERY TECHNOLOGY CAPACITY
SOURCE: RAVELLO V., "ELECTRIC AND HYBRID PROPULSION SYSTEM- LECTURE 4", TORINO 2020

Other issues are linked with the battery disposal and recycle when they are exhausted, it must be closely studied and analysed this spot, indeed the risk is to far reduce noxious and CO_2 emissions on one side while on the other a new important pollutant source could be arisen.

Finally, also the infrastructure presents nowadays must be considered, the importance to recharge rapidly and easily cannot be neglected. About this if the AC/DC charge stations are growing in number in the last years, it cannot be said the same for the recharge speed, indeed, for a partial fast recharge (a recharge strategy that must not be used always due to battery damage risk) at least one hour is needed.

Even if different electric energy sources have been investigated like hydrogen, the guideline followed to overcome the weak points of electric batteries is mainly the coupling of electric powertrain with ICE. The idea is to exploit the electric traction benefits guaranteeing wide range and reliability thanks to classical combustion engine, in this way emissions are reduced but no comfort expenses are paid by customers.

2. Hybrid Electric Vehicle

In this chapter the hybrid electric architecture will be analysed more in deep. The concept explained in the last sentences of previous chapter for which the electric traction motor are used in order to minimize emissions while ICE is exploited as an auxiliary power source can be real but it is not representative of the various and numerous hybrid solutions. Moreover, before describing hybrid electric vehicle, a proper definition must be clarified.

For this purpose, the traction system method introduced by Joseph Beretta is proposed. Following this path, hybrid traction system is defined as a powertrain that joins two or more different elementary traction system. Any elementary scheme must be composed by an energy power source coupled with a related conversion system, an engine or motor, a transmission and wheels.

Knowing these first basilar definitions, simple and complex architectures can be defined as follow:

- Simple Thermal-Electric traction system: it is done by simply linking an ICE based and an electric machine based elementary traction systems. Under this viewpoint two sub-solutions can be highlighted:

    - *Parallel simple thermal electric hybrids* are characterized by a connection at mechanical level, in this way the work produced by both the power source can be exploited directly at wheel. The hybridisation is realized at powertrain level through clutches, joints, chains, gears (direct link) or through the wheel, if two elementary traction system is coupled with two different axes (indirect link).
    This architecture guarantees a high level of flexibility, pure ICE mode and pure electric mode are possible, but, with respect to simple series hybrid, greater cost, weight and volume are experienced. Moreover, since the thermal engine is coupled with the wheel, cannot operate at fixed condition. [9]

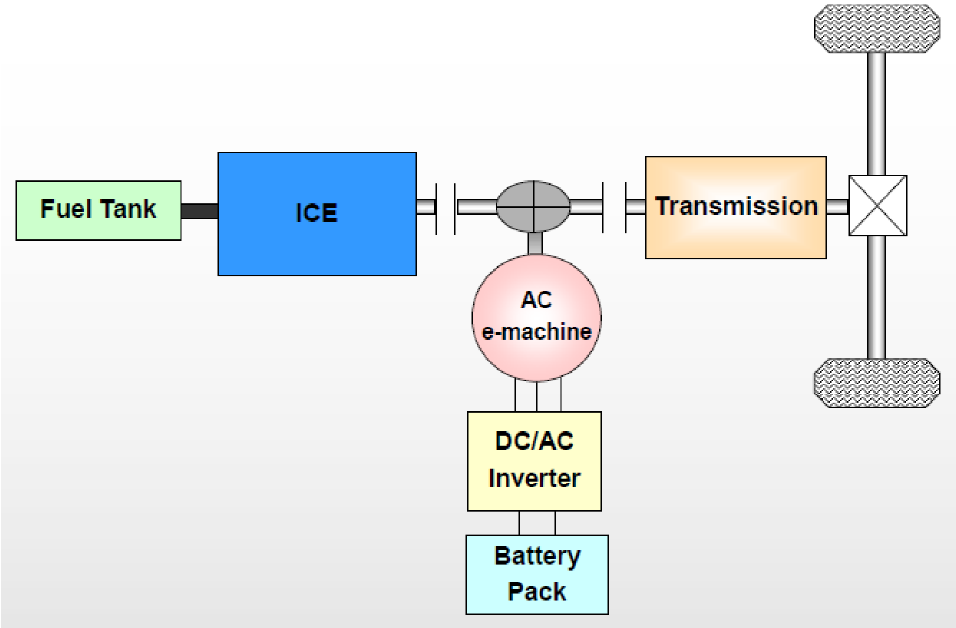


FIGURE 7. SIMPLE PARALLEL HYBRID ARCHITECTURE
SOURCE: RAVELLO V., "ELECTRIC AND HYBRID PROPULSION SYSTEM- LECTURE 15", TORINO 2020

Additional classifications can be done if the position of electric motor is considered:

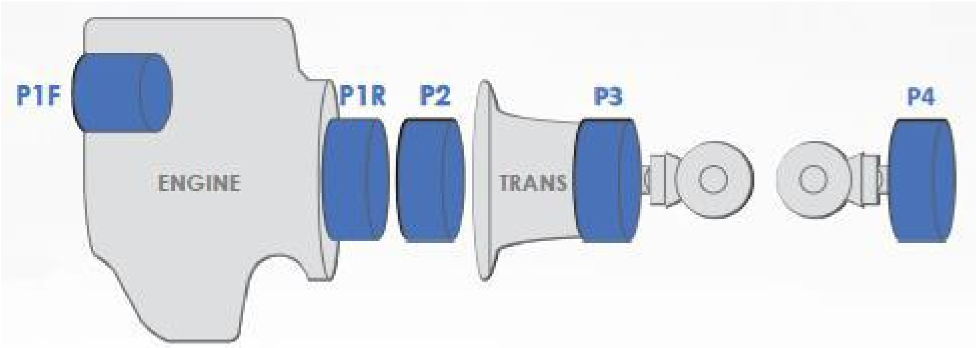


FIGURE 8. P- CLASSIFICATION
SOURCE: RAVELLO V., "ELECTRIC AND HYBRID PROPULSION SYSTEM- LECTURE 15", TORINO 2020

P2 differs from P1R because in the former case the electric machine can be disengaged exploiting the work of a clutch for example, in the latter case, instead, the electric machine is permanently coupled with the thermal engine.

- *Series simple thermal electric hybrids* are done by joining thermal and electric traction system at energy source level, in this case the powertrain that acts on the wheel is only one and it is typically the electric one. The internal combustion engine, in this case, is part of the on-board energy source, it serves exclusively to recharge the battery pack. With this configuration engine could operate at fixed point, maybe in its maximum operating point, reducing emissions, fuel consumption and also noise.
  About this, the Optimal Operating Line is introduced, practically, the engine operating point with respect to the engine speed [RPM] can be chosen in order to allow the engine working at its maximum efficiency point for the considered engine speed. [8]

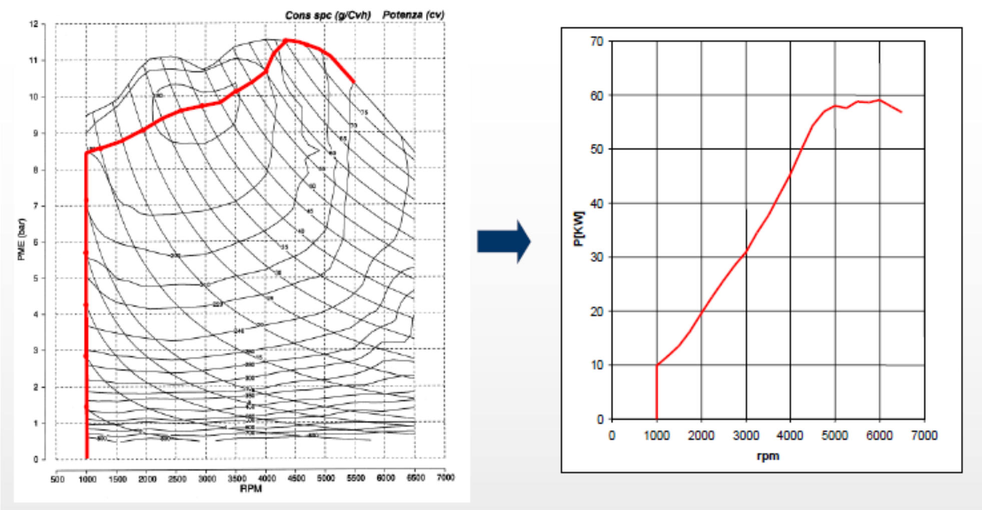


FIGURE 9. OOL- OPTIMAL OPERATING LINE
SOURCE: [8] RAVELLO V., "ELECTRIC AND HYBRID PROPULSION SYSTEM- LECTURE 13", TORINO 2020

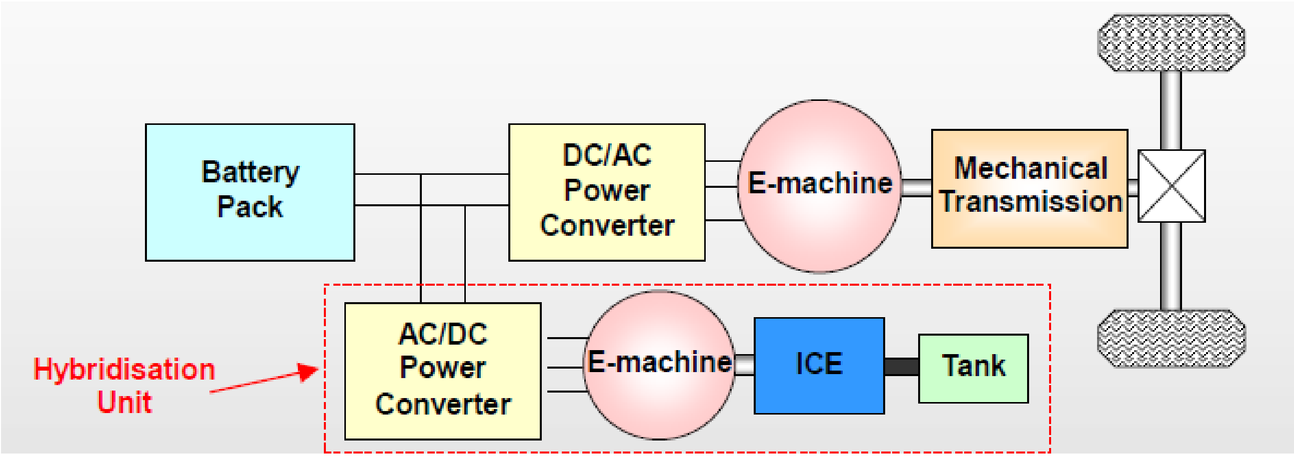


FIGURE 10. SIMPLE SERIES HYBRID SCHEME
SOURCE: RAVELLO V., "ELECTRIC AND HYBRID PROPULSION SYSTEM- LECTURE 13", TORINO 2020

Both simple series and parallel hybrid architecture can be categorized also evaluating the hybridisation degree, basically, the power provided by the two different elementary traction system is defined to understand how the power is produced by the hybrid architecture.
Below the formula for the evaluation in the two different schemes presented are reported: [6]

$$R_{h,parallel} = \frac{P_{ICE}}{P_{EM}+P_{ICE}} \quad ; \quad R_{h,series} = \frac{P_{EGEN}}{P_{EM}}$$

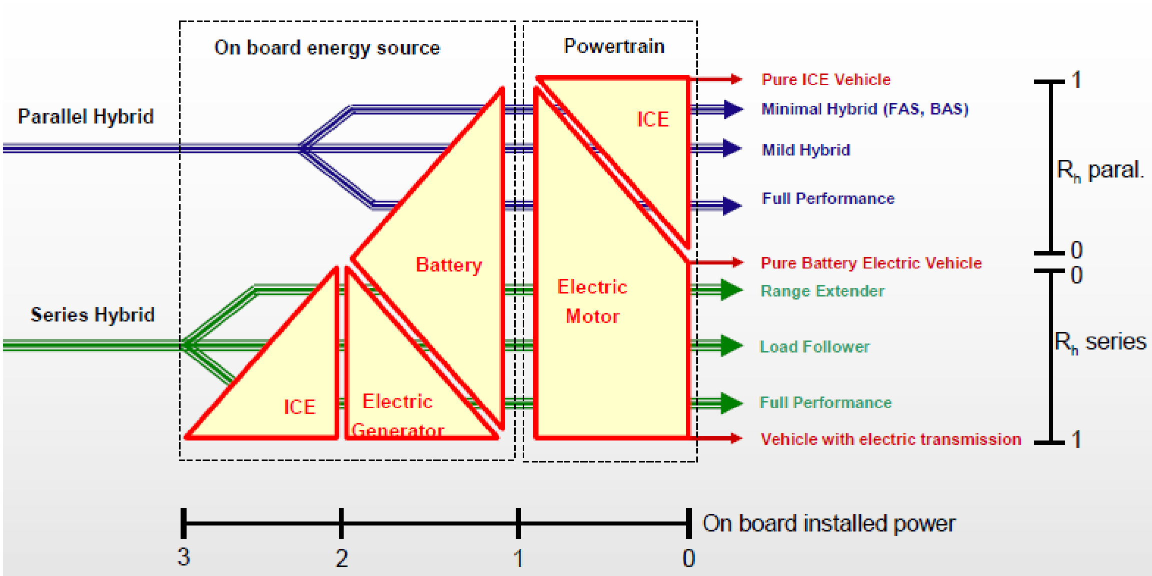


FIGURE 11. HYBRIDISATION LEVEL CLASSIFICATION FOR SIMPLE HYBRID
SOURCE: RAVELLO V., "ELECTRIC AND HYBRID PROPULSION SYSTEM- LECTURE 3", TORINO 2020

- Complex Thermal-Electric traction system: it is done starting by simple hybrid scheme, increasing the number of elementary traction systems or increasing the number of links between different elementary traction system. Also in this case two different sub-case can be seen:
  - *Complex series hybrids* are realized by simply increasing the number of powertrain or on-board energy sources.
  - *Complex series-parallel hybrids* are designed realising two different possible energy pathways. In this scenario, it is possible to have two more other strategy: the first foresees the usage of only one pathway at a time, the second, instead, enables the exploitation of two pathways together.

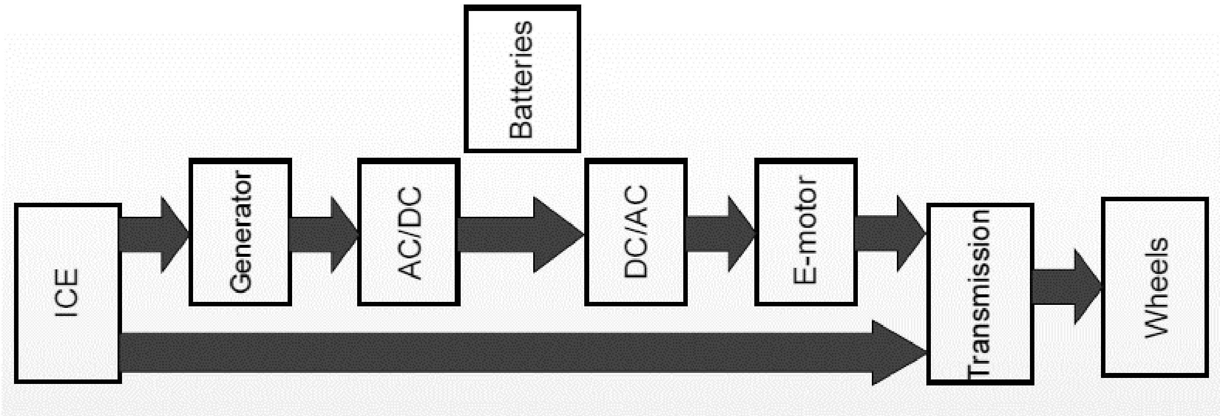


FIGURE 12. COMPLEX SERIES-PARALLEL HYBRID, TWO PATHWAYS EXAMPLE
SOURCE: RAVELLO V., "ELECTRIC AND HYBRID PROPULSION SYSTEM- LECTURE 16", TORINO 2020

In general, it can be said that the complex architectures enable a very high number of possibilities, so the flexibility of these system is a strength. However, this benefit comes at expenses of very difficult control strategies – Electronic Control Unit system could be expen/sive and a complex algorithm must be designed - and overall curb weight increase. [10]

2.1 Range Extender

One of the most interesting solution among the possible thermal electric hybrid architectures is the range extender. As it is previously introduced, this scheme is a simple series hybrid powertrain with a low level of hybridisation.

The internal combustion engine unit is basically introduced in order to provide some power to recharge the battery pack and, doing so, the autonomy can be increased. The baseline is a pure battery electric vehicle, the thermal hybridisation is realised to proper assist the electric propulsion system, for this reason, range extender can also be defined as thermally assisted Battery Electric vehicle.

This configuration ensures a range extension with very low noxious emissions expense, at the same time the battery recharging events can be largely reduced with the consequent benefits. In addition, depending on the number of kilometres that it is wanted to be guaranteed, the battery pack dimensions can be reduced with subsequent improvement under volume, weight, price point of view.

An attractive aspect enabled by this powertrain scheme is the possibility to exploit the thermal engine at fixed point, this means that various advantages can be gained:

- ICE can be always used in wide open throttle mode; this results in a maximum efficiency operating condition. Afterwards, fuel consumption is brought to its minimum.
- Avoiding transient conditions, thermal engine can ensure very low pollutant production level
- Noise and vibration are turned down
- Engine weight and dimensions can be contained

However, some weaker points must be highlighted, they all deal with the battery pack. Indeed, batteries must work continuously in transient conditions, i.e. they are charged and discharged resulting in low efficiency work. Moreover, since thermal engine is designed with the aim of ensuring a certain average range but not to satisfy certain power transient need, the battery pack must cover all the transients and a certain range must be guaranteed too.

One of the most famous and successful example of this type of application is the BMW i3 REX, German OEM's have been capable of designing a performant car with a main electric powertrain that at a same time promises an impressive range of 300 km. The ICE used for the range extension is a naturally aspirated motorcycle-derived engine with 0.647 L displacement and in line two-cylinder configuration; the power provided by thermal unit is 25 kW corresponding to around 23.3 kW available after AC/DC inverter. From experimental and analytical evidences, the contribution given by the engine to the range is around 130 km with an expense of 0.6 l/100 km of fuel. [8]

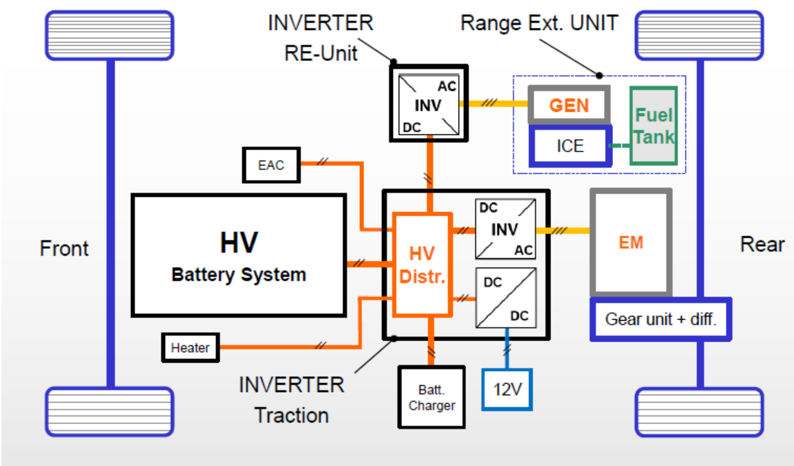


FIGURE 13. BMW I3 REX ARCHITECTURE
SOURCE: RAVELLO V., "ELECTRIC AND HYBRID PROPULSION SYSTEM- LECTURE 13", TORINO 2020

3. Internal Combustion Engine

Up to now a small hint about historical background has been provided and thermal electric hybrid vehicle theories and configurations have been described too. However, since the main objectives of this work concern with the internal combustion engine, its state of the art will be described in this chapter; moreover, a careful focus is reserved for the fuel consumption because it is a characteristic parameter of the internal combustion engine that influences emissions, carbon dioxide production and, obviously, the fossil fuel that is burnt by the engine. Finally, some general widespread strategies finalized to reduce consumptions are presented.

Internal combustion engine aims of producing mechanical power starting from chemical energy provided by a fuel, the peculiarity of this type of thermal motor is that the fuel energy is released inside the engine. Moreover, typically, the internal combustion engines are reciprocating this turns into the practice as almost one piston that moves back and forth inside a cylinder thanks to a combustion chemical reaction (reported in chapter 1.1, equation (1)) that releases energy and acts on the piston; then the plunger, thanks to a crank mechanism composed by a connecting rod and a crankshaft, produces a rotational power. [11]

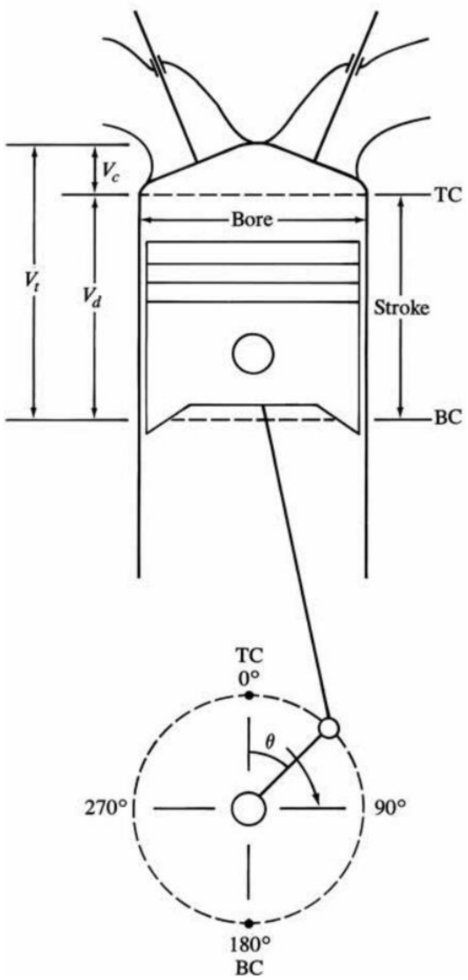


FIGURE 14. PISTON AND CRANK MECHANISM

SOURCE: HEYWOOD J.B., "INTERNAL COMBUSTION ENGINE FUNDAMENTALS 2E" MCGRAW-HILL EDUCATION (PROFESSIONAL), 2019

The two most widespread around the world ICE are the Compression Ignition engine (CI), also called Diesel engine, and the Spark Ignition engine (SI), also known as gasoline or Otto engine. The very important differences between these two engine types are the fuel exploited and the ignition type.

Compression ignition engine uses a low volatility fuel, highly reactive, that has to be converted from liquid state to a vaporized state in order to allow the mixing with air. This process led to an increase in temperature and pressure that is needed to guarantee the autoignition. Definitely, diesel engine experiences a highly heterogeneous process characterized by zones with remarkable differences in composition among them. Moreover, since the fuel spontaneously ignited after a rise in temperature and pressure, an ignition delay is experienced in order to reach the thermodynamic conditions that are needed for the autoignition. Basically, the combustion process in compression ignition engine can be divided in three different phases: the ignition delay, the premixed burning and the mixing-controlled combustion. The first phase concerns with the time that passes between the moment in which the fuel is injected and the time in which the proper combustion reaction starts; premixed burning deals with a highly explosive and abrupt combustion due to the bulk burning of the fuel accumulated during the previous phase (i.e. the ignition delay); last phase, instead, is the step in which the majority of the energy inside the fuel is released thanks to the so called diffusion flame. In a diffusion flame, the fuel mixes with the surrounded hot air and burns typically in a lean air fuel mixing (i.e. the quantity of fuel is less than the fuel in a stoichiometric mix) with a smooth combustion process. [12]

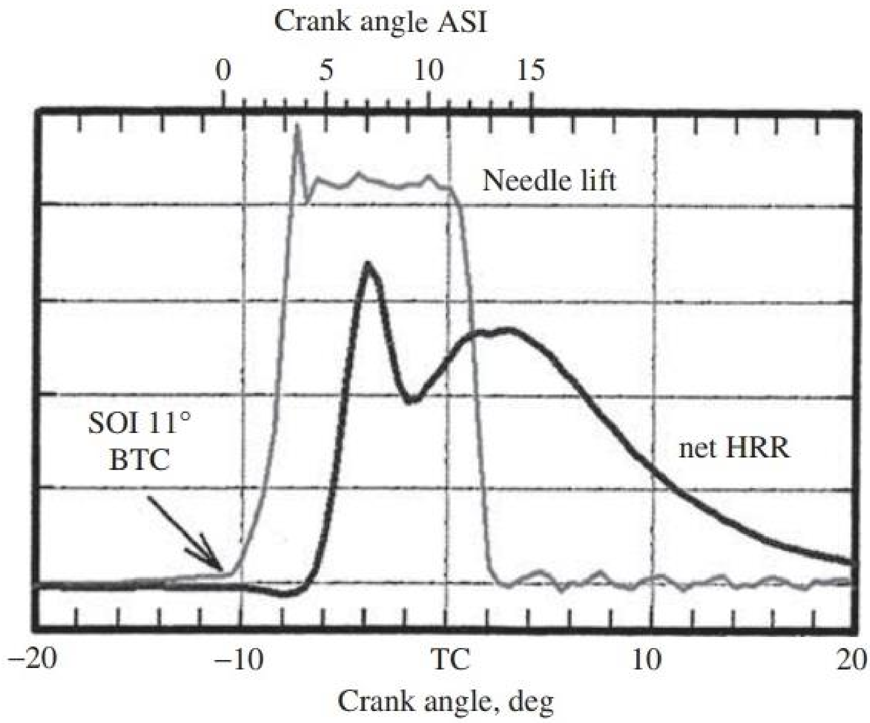


FIGURE 15. EXAMPLE OF HEAT RELEASE DURING DIFFERENT PHASES OF DIESEL COMBUSTION PROCESS
SOURCE: HEYWOOD J.B., "INTERNAL COMBUSTION ENGINE FUNDAMENTALS" MCGRAW-HILL EDUCATION (PROFESSIONAL), 2ND EDITION, 2019

The combustion process described above can also be noted if a typical diesel combustion plume is analysed. Compression ignition combustion plume, indeed, is characterized by a general scheme for which the first portion of fuel out of injector tip is composed mainly by a liquid state fuel, then, when the atomization and vaporization of the fuel begins, the vapor fuel and air mixture can be highlighted. Focusing on the zone in which the fuel has already vaporized, three main portions inside the plume are present: the first part of the vaporized fuel is featured by a rich mixture (Fuel/air≈2÷4), this side of the plume is responsible of the premixed burning phase; the second zone is the mixture present inside the plume, here, due to the lack of air is the cause of the soot production and the combustion process can not be moved ahead. The last portion is the zone composed by roughly the edge of the plume, here the soot present inside the flame enters in contact with the hot surrounding air and the mixing-controlled combustion can take place in lean conditions. [11]

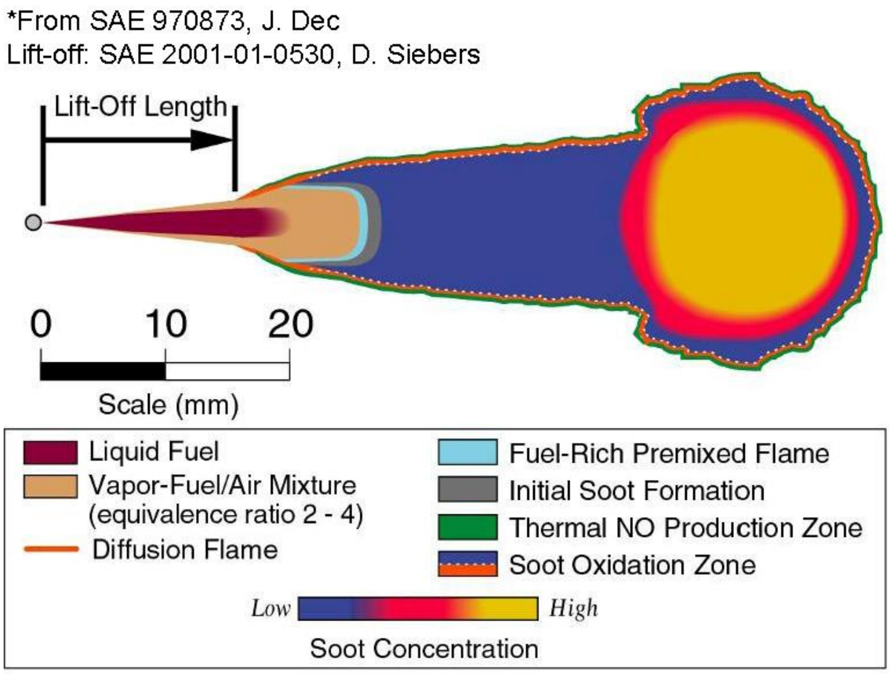


FIGURE 16. TYPICAL DIESEL COMBUSTION PLUME
SOURCE: SPESSA E. "DESIGN OF ENGINE AND CONTROL SYSTEMS-L09-COMB DIESEL", TORINO 2020

Spark Ignition engine differs from the previously presented Diesel engine in two different aspects: the type of fuel exploited and the ignition mode. Gasoline is made starting from the same crude oil of diesel, nevertheless it is a more refined fuel characterized by a massive presence of short hydrocarbons chain (differently from the longer diesel ones), this peculiarity sets the petrol as a low reactivity fuel that, in order to burn, needs an external source of energy for the ignition.

Typically, a spark plug is used to trigger the combustion process, this device is composed of two electrodes one grounded to the engine and another one insulated with porcelain, between these two an electrical discharge is ensured by the spark itself in the portion of space named electrode gap. The electrical discharge that occurs in the electrode gap allows the transfer of energy to the air fuel mixture, causing a ramp increase in the temperature; therefore, the fuel mixed with air in hot condition and under significant pressure can ignite and starts the combustion process that will propagate homogeneously across the combustion chamber. Thinking about what it has just described, another fundamental difference with respect to diesel combustion can be highlighted; in this case, indeed, the injection event is decoupled from the ignition, the fuel is introduced inside the chamber far before the spark discharge in order to ensure a perfect mixture around stoichiometric condition, trying to avoid autoignition and detonation event that in spark ignition engine are not desired since they are the cause of combustion noise and dangerous peak pressure inside the cylinder that could be the cause of engine failure. [11][12]

Both CI engine and SI work, typically, on a four-stroke cycle, this means that, in order to produce power, two complete cycles of the crankshaft and, consequently, four strokes of the piston are required.

1. The first is the so-called Intake stroke, during the travel of the piston from the top dead centre – i.e. the piston position for which the minimum clearance between piston itself and cylinder head is experienced – to the bottom dead centre – i.e. the position that ensures the maximum clearance volume between piston and cylinder head –, the charge is injected inside the cylinder.
2. The second is the Compression stroke, it starts when the piston is at bottom dead centre and ends with piston at top dead centre position. During this phase the charge is compressed and, towards the end of the stroke, the combustion process is initiated.
3. The third stroke is the so known power stroke or expansion stroke, this is the step in which the power is produced, it involves the motion of the piston from the top dead centre to the bottom dead centre position allowed by the energy released by the combustion process.
4. The last stroke involves the exhaust procedure, now the cycle is going to finish, the power has been produced and the exhaust gases trapped inside the cylinder must be ejected from the cylinder, to do this the piston pushes the gases outside through the exhaust valve by moving from the bottom dead centre towards the top dead centre.

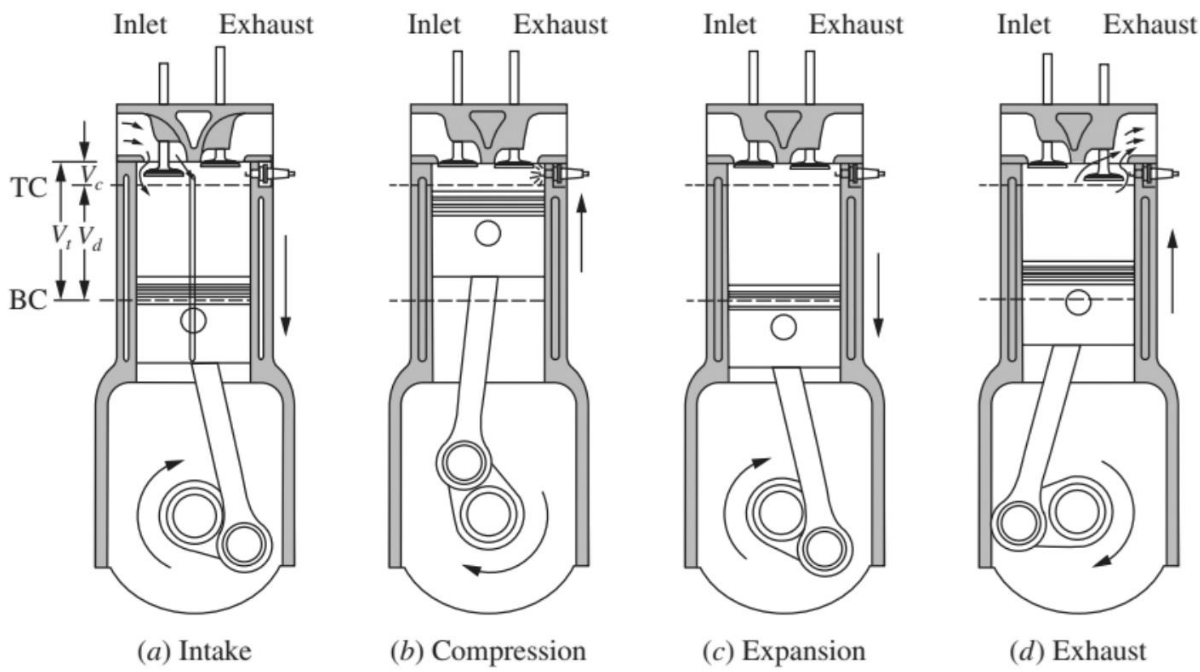


FIGURE 17. FOUR-STROKE CYCLE

SOURCE: HEYWOOD J.B., "INTERNAL COMBUSTION ENGINE FUNDAMENTALS" MCGRAW-HILL EDUCATION (PROFESSIONAL), 2ND EDITION, 2019

To obtain higher power from the same engine displacement and a far simpler architecture with respect to the four-stroke cycles engine the two-stroke engine solution can be adopted. Following this path, the power is produced every crankshaft revolution and so every two piston strokes, the scheme of the engine is simpler since valves are not necessary, indeed, the piston with its movement, opens and closes two ports that act, respectively, as an intake port (transfer port in Figure 18) and as an exhaust port.

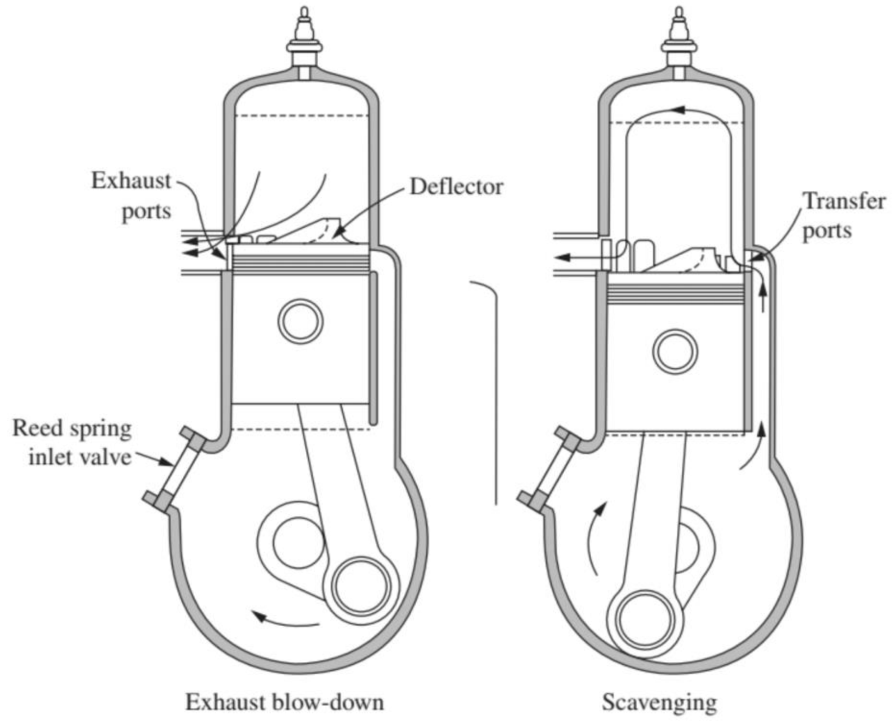


FIGURE 18. TWO-STROKE CYCLE
SOURCE: HEYWOOD J.B., "INTERNAL COMBUSTION ENGINE FUNDAMENTALS" MCGRAW-HILL EDUCATION (PROFESSIONAL), 2ND EDITION, 2019

In this case the two phases of the cycle are:

1. The compression stroke that starts with the closure of the transfer port and then of the exhaust port thanks to the piston movement towards top dead centre. During this phase the charge is induced inside the combustion chamber and compressed simultaneously.
2. The power stroke, that in this case occurs every crank revolution, involves the downward piston movement. Firstly, the exhaust port is opened and burnt gases exit thanks to the blowdown effect; then the transfer port is uncovered and the charge compressed in the crankcase can flow into the cylinder, pushing the remain exhaust gases through the exhaust port. This effect is called scavenging, moreover, in order to avoid that the fresh charge flows directly across the exhaust port, some deflector on the piston for instance can be used.

However, nowadays, two-stroke engines are becoming more and more rare especially in automotive field, this can be explained by their difficult to manage noxious emissions and by a difficult and almost impossible under certain point of view control strategy of the engine operating conditions. [11][12]

3.1 Fuel consumption [15]

As it has been explained in the previous chapters, the main objective and the most important efforts in the powertrain design has been the reduction of fuel consumption. This aspect, as it has been already emphasized, is of paramount importance since less fuel consumed by the engine means less carbon dioxide and noxious emissions production.

Before talking about some smart strategies to save fuel, it must be necessarily introduced what are the main parameters that influences the fuel consumption. Basically, the fuel consumption is strictly related to the power needed to enable vehicle motion at desired speed and, obviously, is linked to the overall powertrain and vehicle efficiencies.

The power required to the engine can be easily evaluated considering three different main contribution, the first one concerns with the rolling resistance provided by the friction between tyres and ground; the second term deals with the aerodynamic resistance and the last share is due to the road slope. For what is related to the first two terms, it can be said that at low speed the main contribution is given by the rolling resistance whereas, when the speeds become higher, the aerodynamic resistance plays the bigger part of the requested power to the engine.

Rolling resistance can be handled considering the dynamic friction coefficient and can be evaluated exploiting this formula (2):

(2) $$Rolling\ resistance = f \sum F_z = (f_0 + KV^2) \cdot (mg \cdot cos(\alpha) - {}^1\!/_2\, \rho C_z S V^2)$$

With f dynamic friction coefficient, m equal to the mass of the vehicle, g gravity acceleration, α road slope (if the grade is different from 0), ρ density of the air, C_z lift coefficient, S front orthogonal surface of the vehicle and V vehicle speed.

Moving on and analysing the aerodynamic resistance contribution, it can be understood why the more the speed is increased the greater becomes the power requested coming from aerodynamic drag. As it can be seen from the computation of the aerodynamic friction, a quadratic term with respect to the vehicle speed is present (3):

(3) $$Aerodynamic\ resistance = {}^1\!/_2\, \rho C_x S V^2$$

With ρ density of the air, C_x drag coefficient, S front orthogonal surface of the vehicle and V vehicle speed.

The last term is present only if the road is not level and so also some power is needed in order to overcome a certain grade (4):

(4) $$Road\ grade = mgsin(\alpha)$$

With m equal to the mass of the vehicle, g gravity acceleration and α road slope.

Summing up these three contributions and multiplying the result for the vehicle speed, the overall power requested by the vehicle can be computed; therefore, to evaluate the actual power that the engine has to provide, only the efficiencies will have to be considered.

(5) $$P_{needed} = \{[mgcos(\alpha) - {}^1\!/_2\, \rho C_z S V^2](f_0 + KV^2) + {}^1\!/_2\, \rho C_x S V^2 + mgsin(\alpha)\} \cdot V$$

Equation (5) can be also rewritten in this way:

(6) $$P_{needed} = A + BV^2 + CV^4$$

where

$$A = mg[f_0 cos(\alpha) + \sin(\alpha)]$$

$$B = {}^1\!/_2\, \rho S(C_x - C_z f_0)$$

$$C = -{}^1\!/_2\, \rho SKC_z$$

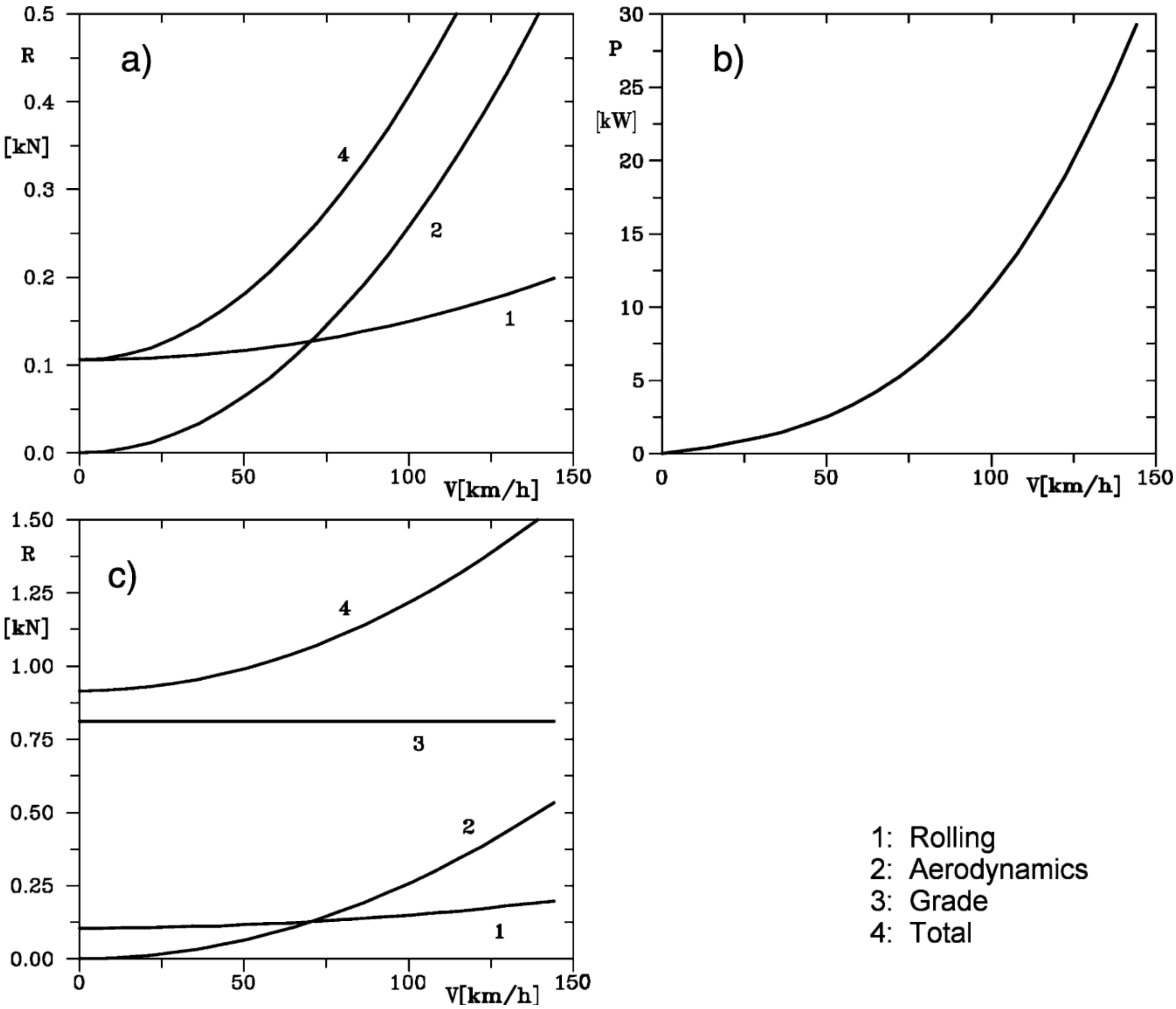


FIGURE 19. FORCE AND POWER REQUESTED WITH RESPECT VEHICLE SPEED
SOURCE: GENTA G., MORELLO L., "THE AUTOMOTIVE CHASSIS VOLUME 2: SYSTEM DESIGN", SPRINGER, 2009

Knowing the power needed, it can be finally evaluated the fuel consumed by the engine, to achieve the result the lower heating value of the fuel LHV and the fuel density ρ_f must be considered, obviously, as it has been introduced before the overall efficiency of the engine η_e and overall efficiency of the transmission η_t must be considered:

(7)

$$Q = \frac{P_{needed}}{\eta_t \eta_e LHV \rho_f} = \frac{AV + BV^2 + CV^4}{\eta_t \eta_e LHV \rho_f}$$

Fuel consumption can also be evaluated taking into account the specific fuel consumption of the engine $q(T_e, \omega_e) = \frac{1}{LHV\eta_e}$:

(8)

$$Q = \frac{qP_{needed}}{\eta_t V \rho_f}$$

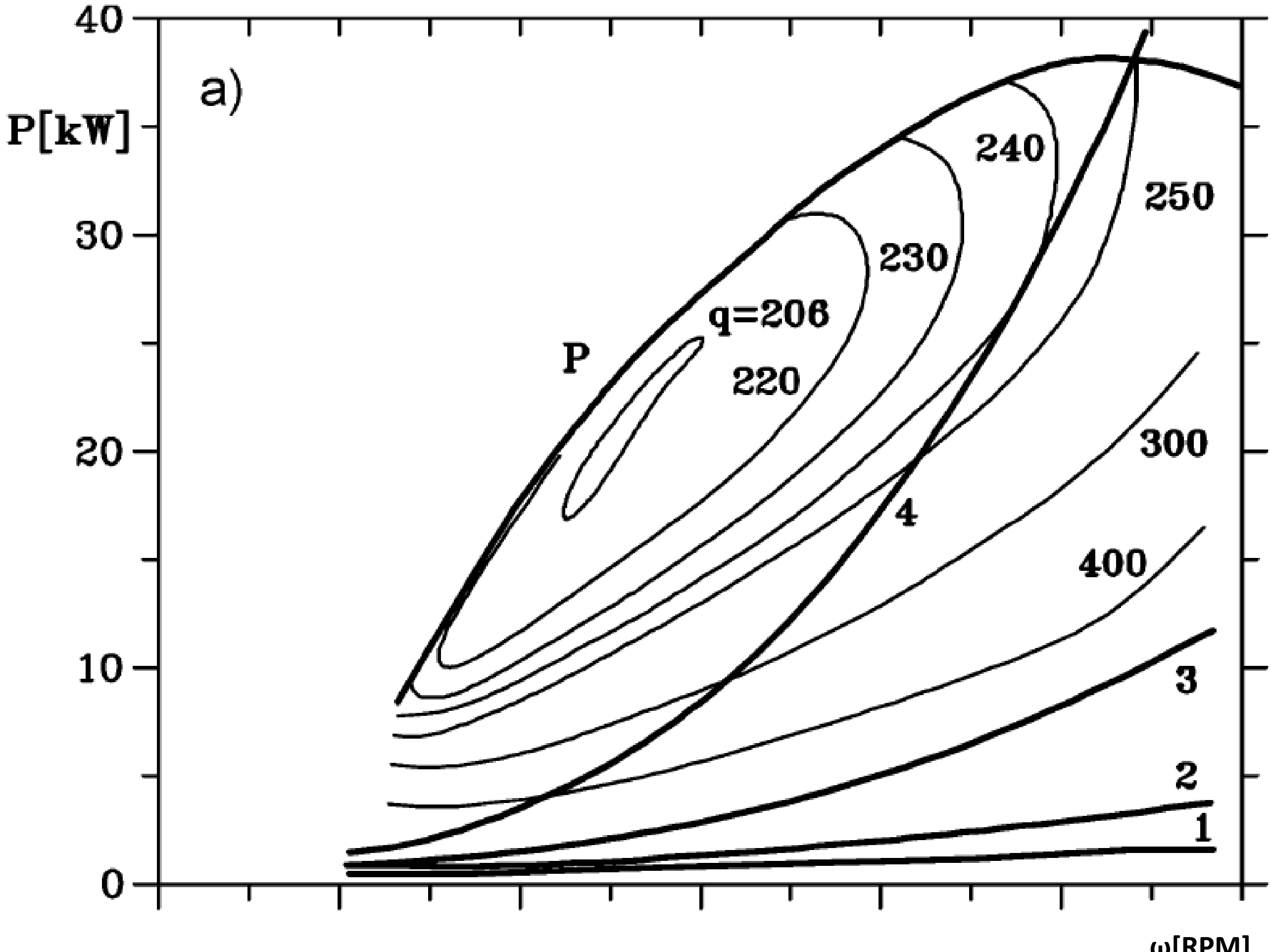


FIGURE 20. ENGINE MAP WITH POWER NEEDED CURVE EXAMPLE
SOURCE: GALVAGNO E., "POWERTRAIN COMPONENT DESIGN- TRANSMISSION LECTURE 2", TORINO 2020

3.2 Engine performance optimization strategy

As it can be understood from previous paragraph, the two easiest way to reduce and optimize fuel consumption are an efficient aerodynamic design and an important weight reduction, these two actions seem to be the two more obvious path in order to reduce car consumption. However, not always it is possible to act following these ways, the reasons could be linked to the consequent detrimental effect that a modification in the chassis design can lead or, more frequent, a more important economic effort. To be clearer, it can be experienced, for instance, some issues with cockpit comfort or, simply, a new chassis design could cost very large amount of money and could require change in almost all the others car components.

Knowing these premises, it is evident that, to reach the goal of a thriftier vehicle, it is necessary to work on engine performance and management strategies. Nowadays, since the internal combustion engine technology has been studied from many years and it can be regarded as a “mature” innovation, a good number of methodologies are known, and deeply studied, to make thermal motor efficient and so less fuel consuming.

The very first innovation introduced with fuel saving target is the valve variable actuation and lift, this technology foresees the usage of a suit valve timing for each engine cycle, following this path a customized mixture can be achieved depending on the engine load and speed, moreover, some effects can be pursued in order to facilitate different fluid dynamic phenomena. Going more in deep in this aspect, a smart valve timing and actuation system pursues the best trade-off between fuel consumption and performance, this means maximising fuel saving when high performances are not required meanwhile ensuring good performance when the driver wants power and reactivity.

Before explaining how a good valve timing could be designed, some fluid dynamic phenomena must be introduced, blowdown will be introduced firstly and then the losses related to the pumping procedure will be presented.

The blowdown process concerns with the substitution of the exhaust gases inside the chamber with the fresh charge when a cycle is going to finish while a new one is starting. Basically, this process exploits the pressure difference that exists between fresh charge and exhaust gases in order to push out the formers, that are already present in the chamber when the expansion phase is ending. The pressure in the combustion chamber, indeed, is higher than the one in the exhaust system allowing a natural flow of the residual outside ensuring, at the same time, that the fresh charge reaches the combustion chamber. However, it should be clear that the pressure gradient could not be positive forever and it could not be so efficient for long time too, even more considering the expansion movement of the piston that, obviously, penalises the pressure inside the chamber. In particular, depending on the load, different timing for the exhaust valve closure and for the intake valve opening could be highlighted. It is possible to say that for each load exists a perfect time to optimize both fuel consumption and performances, however, as a general rule could be said that the sooner the exhaust valve is opened, the greater the expansion work is minimized resulting in a general worsening of the thermal efficiency. Moreover, since the valve overlap – i.e. the period in which both the exhaust and the intake valve are opened – is increased, some fuel could be wasted due to the so called short-circuit flow. This phenomenon involves an extremization of the scavenging process for which beyond the exhaust gases also a portion of fresh charge is pushed directly in the exhaust manifold. This speech suggests that, in order to save fuel, the exhaust valve opening must be retarded as much as possible at part load while, at the highest load, prompts an early opening.

Unfortunately, blowdown is not the only process that must be accounted for, indeed, also pumping losses must be considered. This aspect involves a massive power leakage due to the work handed out for the introduction of fresh charge inside the cylinder. This loss becomes important especially at low load due to the higher presence of residual gases inside the chamber that getting worse the combustion process. Moreover, in throttled engines, at partial load, an important pressure loss is caused by the throttle valve itself that, in order to manage the right mixture preparation, reduces pressure inside the intake air duct worsening the intake procedure that is led mainly by the pressure gradient between the duct and the chamber. With a valve variable timing and actuation, a short intake duration allows to work unthrottled drastically reducing the pumping losses. The only limitation concerns with the mixture preparation that it must be carefully considered in this case. [14]

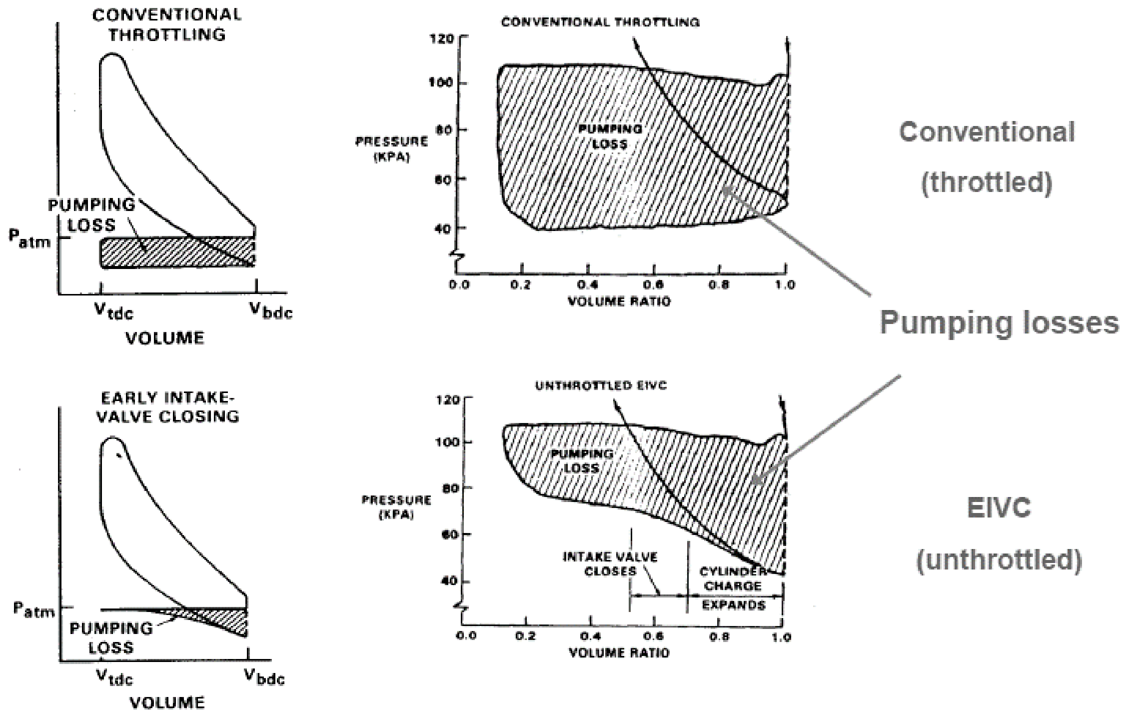


FIGURE 21. PUMPING LOSSES WITH THROTTLED AND UNTHROTTLED (VVA) DEVICE
SOURCE: MILLO F., "ENGINE EMISSIONS CONTROL-GASOLINE FUTURE DEVELOPMENT", TORINO 2020

In general, it could be said that with valve variable actuation different valve lift and timing could be achieved in order to reach the same objective of fuel saving. To get to the desired result, OEMs in the last decades have implemented different strategies to handle the right managing of the valves operations patenting different interesting solutions that are adopted still nowadays.

Another strategy to improve fuel saving is the combination of turbocharging and downsizing. This strategy is particularly popular in the last years due to its simultaneously fuel expense reduction and good noxious emissions behavior.

The downsizing consists in the reduction of the engine displacement ensuring, exploiting other systems, the same power of the original engine. As a rule of thumb, a smaller volume guarantees by itself less fuel consumption still, downsized engine works, at lower load, in engine map with higher efficiencies with respect to the base engine.

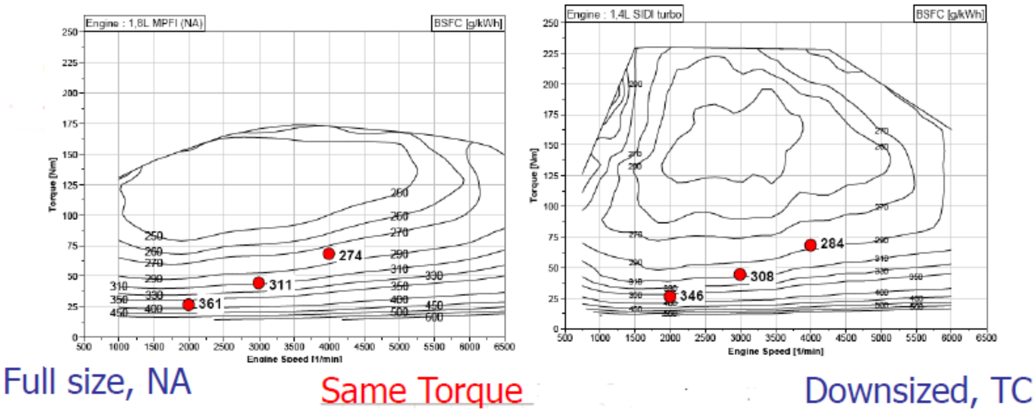


FIGURE 22. COMPARISON BETWEEN A NATURALLY ASPIRATED ENGINE AND A SAME ENGINE DOWNSIZED
SOURCE: MILLO F., "ENGINE EMISSIONS CONTROL-GASOLINE FUTURE DEVELOPMENT", TORINO 2020

Up to know a downsized engine could be a smart choice, however, without an alternative strategy is impossible to ensure the same performances of a bigger engine, turbocharger makes up for it and compensates the performances hole caused by a smaller cylinder displacement. Practically, a turbocharger is a device that, exploiting the remaining energy inside the exhaust gases, compresses the fresh air intaken. Fresh air at higher pressure achieves better volumetric efficiency, more air inducted in the cylinder and, consequently, better performances than a same naturally aspirated engine. In the chapter four, supercharging devices will be further analyzed.

4.Engine Management and layout

Up to now the theory and the state of the art of the hybrid electric vehicle have been presented, moreover, a general overview about internal combustion engine has been provided, in this chapter the core of the thesis project starts to be explained.

As it has been previously said, the engine design is at an advanced point, in the last four years the main components of the hybrid powertrain have been studied and projected carefully improving them constantly. The final general solution concerns with a range extender architecture, two electric motor are located on the balancing countershaft of the thermal engine while a third generator is placed on the turbocharger shaft in order to grab energy also from the residual gases work that has not been exploited from the compressors.

A dedicated paragraph must be necessarily reserved for the internal combustion engine. The thermal unit of the hybrid architecture, indeed, shows a lot of innovative solutions and ideas that have led the study to very successfully results in terms of power, fuel consumption and trade-off between the twos. The engine configuration is a boxer (or opposite) one, this setup is a particular V solution in which the angle between the two banks is equal to 180 degrees. For the sake of clarity, it must be explained that in an engine when, more than one cylinder is present, they could be organized in a lined configuration or in two (V engine) or three (W engine) rows – the banks – divided by an angle that in this case is equal to 180 degrees.

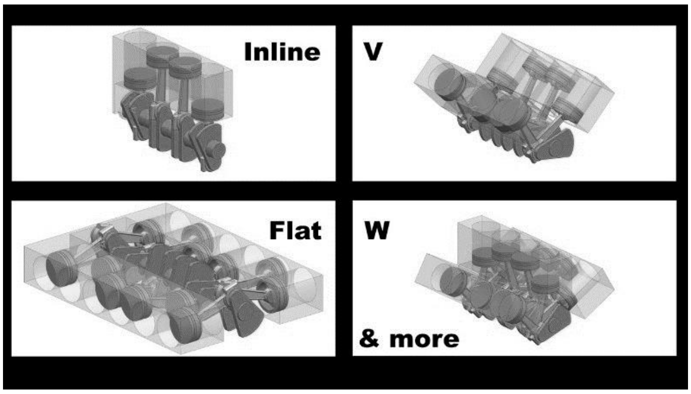


FIGURE 23. ENGINE CONFIGURATIONS

The ICE is highly downsized with a 0.125 L displacement, moreover, the volume is strongly split too in four cylinders divided in two banks. In this kind of architecture, the thermal engine must be almost "invisible" ensuring the desired energy demand with the lowest possible fuel consumption and emissions. The choice of a very small power unit is the most logical one, the motor can be designed in order to work at a fixed point guaranteeing the maximum energy production with the best efficiency possible and the lowest noise emissions.

To reach those goals, other two groundbreaking ideas have been adopted, the first deals with the engine management, indeed, in this case the Miller cycle has been exploited; the second, instead, it could be also more innovative: if the Miller cycle in the last years have been more and more widespread in downsized turbocharged spark ignition engine, the same could not be said for the adoption of an axial turbocharger in an automotive application.

Interesting aspect for the cost saving in production are a mountable crankshaft and a tunnel basement, the first solution allows to produce the component starting from a semi-finished product, deleting the cast costs. Moreover, with a mountable crankshaft the conrod can be made in one piece, facilitating the production process. The tunnel basement is another possibility guaranteed by this type of crankshaft architecture and it allows to produce the element exploiting an extrusion process.

Oil used as cooling liquid, distribution transmission designed with a gear system are some other revolutionary and unusual concept that have been implemented during the project and that will not be explained in deep in this work since it is not part of itself.

4.1 Turbocharger

With a strong downsizing like in this case, the usage of a turbocharger, indeed, becomes practically necessary in order to achieve the desired power and energy output.

The concept of supercharging involves the increase of the air pressure intaken inside the cylinder in order to improve the volumetric efficiency and consequently the engine performances and consumption. Moreover, supercharging allows to enjoy the scavenging effect, for which the process of substitution of the residual gases inside the chamber with the fresh charge is facilitated thanks to the higher pressure of the air intaken; this positive differential pressure allows to push the residual gases towards the exhaust manifold, meanwhile facilitating the entrance of the new mixture inside the chamber. Practically, the air is compressed by a compressor that, in supercharged solution, is driven directly by engine or by other device, instead, when it is talked about turbocharger, it is intended a compressor linked, and so moved, by a turbine that exploits the energy provided by the exhaust gases. [16][17]

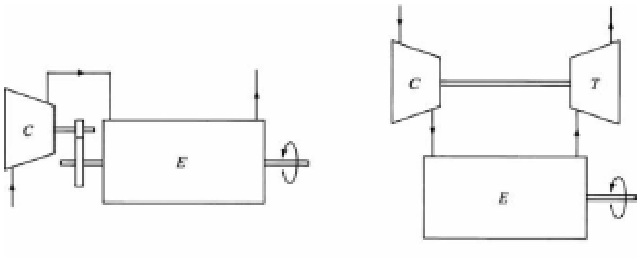


FIGURE 24. SUPERCHARGING (LEFT) TURBOCHARGING (RIGHT) SCHEME
SOURCE: HEYWOOD J.B., "INTERNAL COMBUSTION ENGINE FUNDAMENTALS" MCGRAW-HILL EDUCATION (PROFESSIONAL), 2ND EDITION, 2019

Basically, turbocharger could be subdivided in two main groups: centrifugal or axial with the former widely adopted in automotive field for their good performances in transient conditions – the most frequent background during car usage – the axial solution on the opposite, ensures very high efficiency with respect to the centrifugal case (≈80%) but very slow response in case of transient situations.

Physically, the main difference between the two is the geometry, in the first case, indeed, the entry directions of the fluid inside and outside the turbomachine are perpendicular; in the second situation, on the opposite, the fluid enters the turbomachine in a direction that remains steady across the machine.

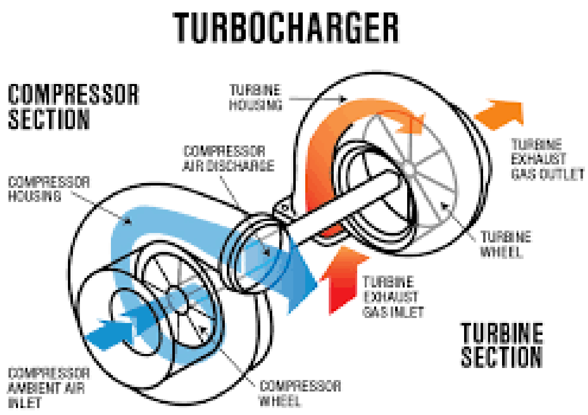


FIGURE 25. CENTRIFUGAL TURBOCHARGER FLUID SCHEME

SOURCE: OCCHIPINTI A., "RADIAL TURBINE GEOMETRICAL PARAMETERS OPTIMIZATION BASED ON CFD ANALYSIS AND APPLICATION TO ENGINE PERFORMANCE ASSESSMENT", 2019

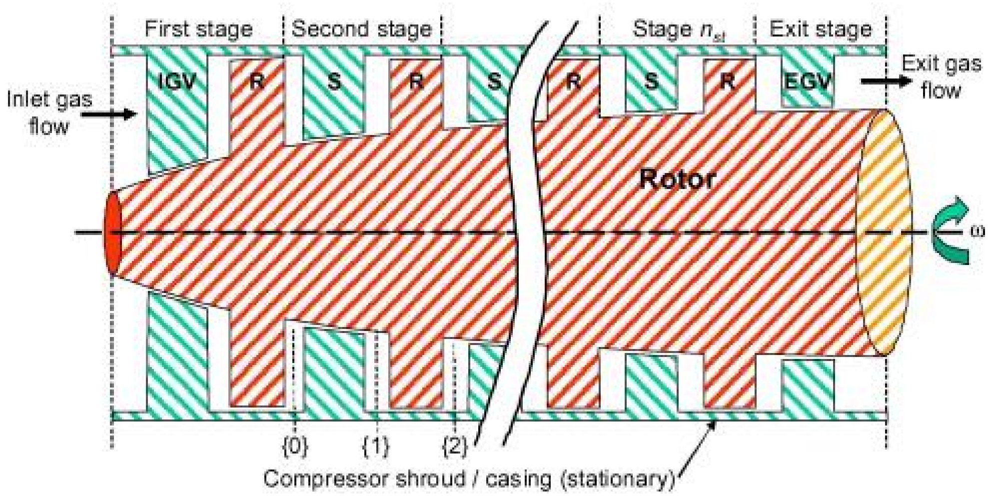


FIGURE 26. AXIAL COMPRESSORE SCHEME

SOURCE: TOURNIER J.M., EL GENK M.S., "AXIAL FLOW, MULTI-STAGE TURBINE AND COMPRESSOR MODELS", 2008

These premises suggest to exploit a centrifugal solution, in conventional engine, indeed, is still the most adopted one; however, since in this case the ICE is thought to work at a fixed point to produce electrical energy, the choice of an axial configuration could be winning and the results obtained in the previous works give reason to the native idea.

The final turbocharger design, obtained after four different works of project and optimization performed in previous work by Eng. Giorio, Eng. Obertino, Eng. Celoro and Eng. Pochini, is characterized by three compressors composed by 7 stages – i.e. the coupling between rotor and stator - the first, 7 stages the second and 8 stages the last one. Compressors will be moved by a turboshaft linked with a single turbine composed by 7 stages and a final diffuser that allows a lower pressure at the turbine outlet, which improves the turbine expansion ratio, resulting in a higher specific work transferred from the fluid to the turbine. In addition to these features, three heat exchangers are used to lowering the temperature of the gases increasing the pressure; the intercoolers are placed after each of the three compressors. At last, it must be quoted also the electric motor that is linked with the turboshaft and allows to produce some energy from the remaining not exploited residual gases work; the generator is placed between the second and the third compressors. From Eng. Pochini's work, the pressure of 12 bars – the target boost pressure – has reached with very high value of compressors efficiencies respectively equal to 0.850, 0.840, 0.826. Also, the turbine shows an impressively 0.836 efficiency value. [18]

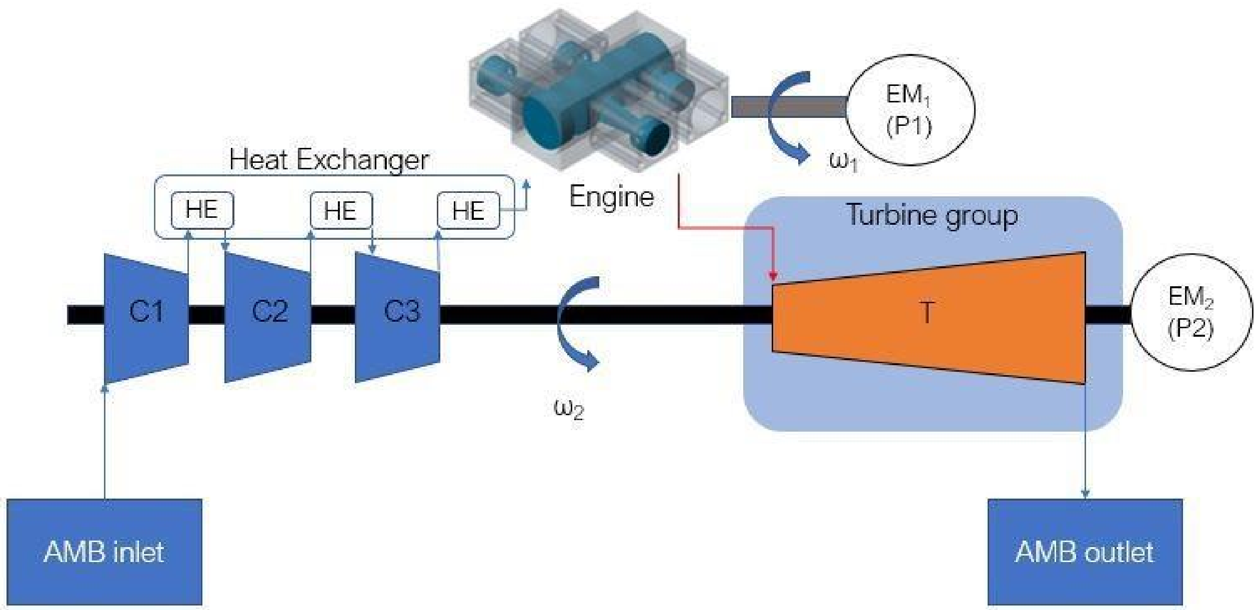


FIGURE 27. SCHEMATIC OF THE TURBOCHARGER GROUP

4.2 Miller cycle

The internal combustion engine object of this project exploits the Miller cycle, this kind of cycle is based on the Atkinson patented cycle. The idea behind this kind of cycle is to improve the indicated fuel conversion efficiency by means of an overexpansion stroke, therefore, with respect to a base cycle in which the duration of compression and expansion is equal, the power stroke in this case is longer than the compression one. This kind of management is particularly useful, in terms of fuel consumption, at lower load achieving fewer pumping losses; moreover, an overexpanded cycle is prone to be very useful also for the knock mitigation. Knock is an undesired phenomenon that could occurs in spark ignition engine, practically, it involves the abrupt detonation of the mixture before the spark triggers the charge, leading to dangerous pressure peak that in turn could damage the engine component. As it could be already understood, a turbocharged engine likes the one object of this work, it is more prone to this unwanted phenomenon, since higher pressure is reached during combustion process. These two positive aspects suit perfectly the goals of the engine under development, for that reason, the choice of using this kind of cycle appears to be the more natural. [19]

However, Atkinson patents his cycle in 1887, obviously, the target mechanical system was not an automotive internal combustion engine but a particular packing, nevertheless, his studies are very well suited also for the car design. Still, Miller, in 1957, went more in deep and patents a specific overexpanded cycle for car vehicle and for otto cycle in particular. Since to obtain different geometric strokes for compression and expansion could be difficult in terms of design and production, it is smart to work on the effective compression one. This means operate on the cycle and, in particular, on the valve timing in order to obtain the desired cycle with different compression and expansion ratio, to do this, a variable valve actuation system is mandatory.

To obtain an overexpanded cycle working on the valve timing, two different strategies could be implemented, the first involves an early intake valve closure (EIVC) while the second concerns with a late intake valve closure (LIVC). The main results obtained are shared between the two different methodologies: better efficiency, less indicated fuel consumption, lower charge temperature that in turn ensures a substantial mitigation of knock occurrence at the expenses of power output that is a little penalised. However, the two strategies show some differences between each other, indeed, if the EIVC reduces the pumping losses and so the fuel consumption at low load, the same cannot be said for the LIVC strategy for which a substantial fuel saving is guaranteed at higher loads. Moreover, the late closure guarantees a better fuel mixing and a smoother combustion with respect to the early closure, in this case, indeed, the charge is expanded as soon as it enters in the chamber and a turbulence deterioration and, in some cases, also a fuel vaporization hindering is experienced. Also, LIVC shows a more promising knock mitigation, ensuring in addition a more spark advanced resulting in a less delayed combustion and with a leaner mixture. [20]

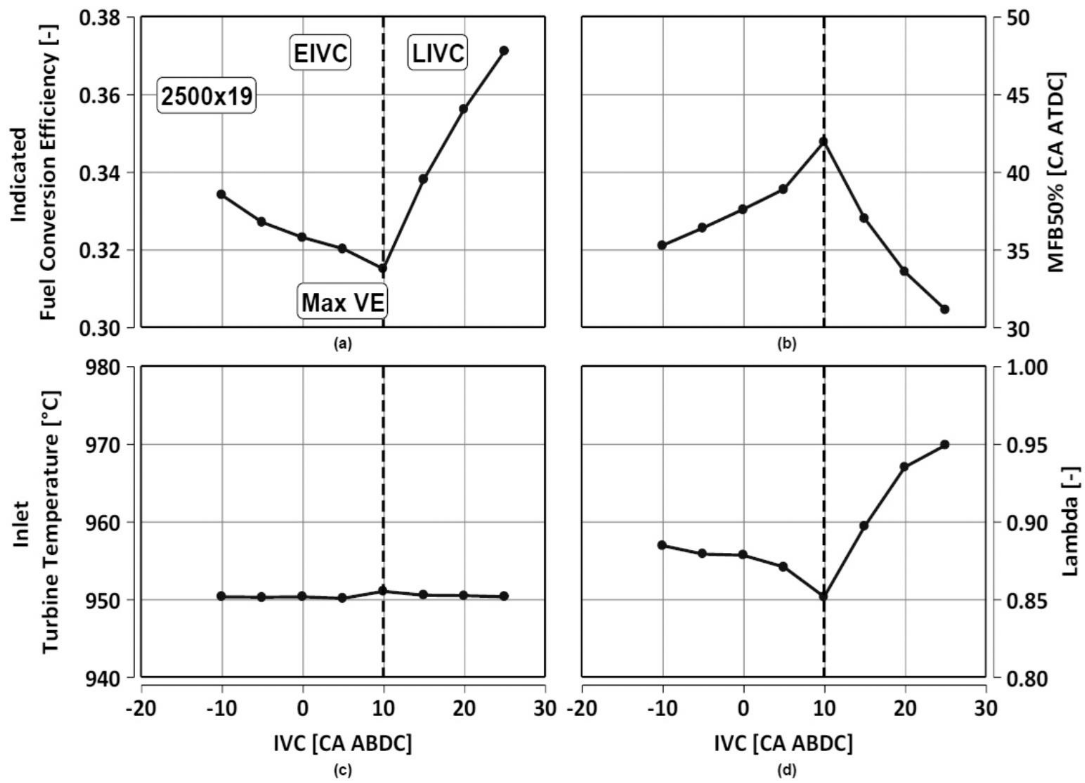


FIGURE 28. EIVC AND LIVC STRATEGIES COMPARISON FOR MILLER CYCLE

SOURCE: [20] LUISI, S., DORIA, V., STROPPIANA, A., MILLO, F. ET AL., "EXPERIMENTAL INVESTIGATION ON EARLY AND LATE INTAKE VALVE CLOSURES FOR KNOCK MITIGATION THROUGH MILLER CYCLE IN A DOWNSIZED TURBOCHARGED ENGINE," SAE TECHNICAL PAPER 2015-01-0760, 2015

5. Cost Analysis

The cost analysis process, also known as product value analysis, was born during 1940s due to the lack of raw materials and products as a consequence of the second world war; this needed has been traduced in the creation of some new methodologies in order to make up for these problems. From that period, the value analysis has been grown exponentially and it has new targets such as the minimization of cost, the search for some critical aspects, under economical point of view, before the physical start of production and, also, it becomes essentially for foreseeing the expected investment and general expenditures. It can be exploited also for the optimization of an already manufactured product. Moreover, if a good work is performed, the best trade-off between the product quality and the manufacturing cost could be achieved. Some worldwide companies like Toyota, Nissan and Hitachi have a dedicated team of engineers aims of studying and taking decision for an optimized production. [21]

Depending on the targets of the analysis, different aspects can be analysed; if, for instance, a company is thinking of developing a new product in an already existing and productive site the parameters that must be accounted for in the analysis will be related to raw material costs, labour costs – i.e. the money dedicated to the new workers' wages –, the investment related to new tools and, eventually, industrial machines must be analysed too. Otherwise, if the product is totally brand new and the manufacturing must be organized in a new facility, a wider analysis must be led considering all the variables that makes up for such an investment: building costs of purchase or rent, the country in which the product will be manufactured and the general costs linked to administrative office are some parameters that have to be necessarily taken into account.

The investments faced up for the product can be grouped in two categories:

- Direct cost: in this category all the cost related to the product and to the transformation of it must be analysed, this includes raw material, labour and machines exploited for the manufacturing and related maintenance and tools.
- Indirect cost: under this name are subscribed all the voices related to overhead expenses, administrative offices, facilities and handling of the material and products.

Raw material evaluation includes the cost for the production or for the semi-finished item from which the product is started to be manufactured. This parameter is influenced by the amount of material that is wasted during the transformations and by the quantity that can be recycled and reused for other applications. Different ways exist to model these values for cast or machining processes.

Labour cost is simply the amount of money invested for the workers' wages and for, eventual, travel or general refund sustained by the employee. It is important to take in mind that even if, for some reasons like maintenance or failure, machine cannot work, the amount paid to the subordinate does not change. In this work, all the salaries refer to 1920 hours of work per years, moreover, since the shift considers in a day are two, it is often accounted for 3840 hour of work per year.

For what deals with the machines, it has considered a four-year depreciation, this means that each year the 25% of the initial investment is charged to the product. The overall year costs of the tools are subdivided over the time of utilization – i.e. the 3840 hours quoted above - multiplied for the productive time machine evaluated in 85%.

A clarification must be, instead, given for the overhead expenses term, with this concept, indeed, is intended all the costs that cannot be clearly identified and charged to any specific parameter. Certain book refers to overhead expenses also as indirect or general expenses.

It can be said that overhead expenses are generally modelled considering a percentage of the cost related to the direct cost for which are evaluated. Those general costs, indeed, can be further subdivided: if, for instance, is considered the engineering department of a company, it is possible to group under overhead the costs for procuring computer, software, programs' licenses. To model this kind of expenses, a fraction of the engineering department costs is considered. Even if it could be thought about overhead as secondary and little part of the overall expenses, it can be said that, generally, they can run also between 200% and 400% of the direct labour cost of the department considered.

Talking about administrative cost, instead, it can be calculated following a similar path to that of direct cost: the employees' wages are considered with the tools and machines needed for the administrative offices

The last point it is the more variable, indeed, for what deals with the handling of the material, the costs vary with the kind of transportation chosen for the factory. However, in this case, the cost of the machinery, its maintenance and the source of energy that it exploits must be taken into account. [22]

The analysis conducted on the object components– i.e. the cylinder head, the turbocharger, the basement and the crankshaft – of this thesis involves mainly the evaluation of the direct cost.

The path followed for each part work is basically the same: the starting point of the analysis has embroiled the drafting of the bill of material, for this aspect the next chapter could give a deepening, next, each assembly has been analysed starting from the evaluation of weight and material costs. About materials' costs an important bracket must be opened: the evaluations and the calculations reported in this essay are referred to the actual market cost (2021 first semester), this is an important aspect since the cost per kilogram is floating and, in this particular period, after the pandemic, the values have reached very high peak; in a future if a perfect result will be requested, material cost voice must be revised surely due to the market fluctuations.

The last part of the analysis has been the longer since the manufacturing process has been considered, for this reason working cycle have been studied in order to understand the machining time and the consequent expenses. Moreover, where a cast process is foreseen, also the timing for the die production, melting of the metal and all the step needed for the casting have been calculated. This aspect is of crucial importance for the evaluation of the number of machines, tools and labour needed to satisfy the target production per year for each component. The goal of this work is to evaluate the cost to produce a number of components that satisfy the requirement of 20 000 engine per year.

In this chapter, the procedure of the analysis has been provided, moreover, the materials' costs, the hourly cost centres for the various departments have been obtained and reported. In the next chapter, the results gained will be ordinated and the final costs for the production of each single items will be provided.

5.1 Engineer Bill of Material (EBoM)

When it is talked about Engineering Bill of Material, it is intended the document or the process that includes the encapsulation of all the components that make up a mechanical device. Basically, it is a sort of recap of all the parts that compose an assembly, moreover, it has the task of specifying the quantity of each piece.

The Engineering Bill of Material born, usually, at a design level and it gets all the information from CAD parts and/or assembly and from the drawings arising.

Normally, it is designed in different levels, this is an important peculiarity because from that hierarchical representation, it can be highlighted the parts that make up for a subassembly, the subassemblies that make up for an assembly and so on, up to the point in which the biggest possible system is individuated. It is possible to transform it also in a flowchart.

For this reason, it can also be thought as a mounting procedure organizer, looking to its structure it is possible to understand the smarter way to organize the composition procedure. [23]

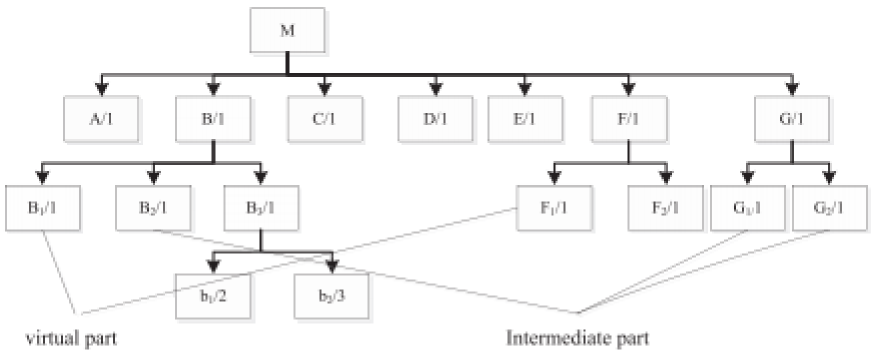


FIGURE 29. GRAPHICAL STRUCTURE OF EBOM
SOURCE: LIU M., LAI J., SHEN W., "A METHOD FOR TRANSFORMATION OF ENGINEERING BILL OF MATERIALS TO MAINTENANCE BILL OF MATERIALS", ROBOTICS AND COMPUTER-INTEGRATED MANUFACTURING VOLUME 30, ISSUE 2, APRIL 2014

Moreover, it appears clear the utility and the needed of such a tool for the present work, it has been the starting point of the research and it has been useful during all the work. In order to design all the processes, to evaluate the number of machines, workers and tools, it has covered a fundamental role. An example is given by the fact that, it is true that the target number of engines has already been fixed, but the amount of each components could not be the same of the 20 000 target engine; for instance, valve commands are 4 for each cylinder and so 16 per engine, it means that, for 20 000 engine, 320 000 valve commands are needed per year!

This premise confirms and sustains the needed of an accurate EBoM for the engine under development, moreover it reinforces its position as starting work point.

Below it will be reported the Bill of Material of the components analysed in this work, however, the entire range extender power unit has been pointed out during the analysis progress.

Cylinder head assembly				
	Head with fixed elements (4)			
		Cylinder head		
		Intake valve seat (2)		
		Exhaust valve seat (2)		
		Valve guide (4)		
	Engine valve			
		Valve seat gasket (16)		
		Intake valve assembly (8)		
			Intake valve	
			Intake valve spring	
			Intake valve retainer	
			Locks	
			Rocker arm assembly	
				Hydraulic tapper for rocker arm
				Rocker arm
				Roller
				Mounting clip
		Exhaust valve assembly (8)		
			Exhaust valve	
			Exhaust valve spring	
			Exhaust valve retainer	
			Locks	
			Hydraulic tappet for direct acting	

TABLE 2. CYLINDER HEAD ASSEMBLY BOM

Turbocharger		
	Shaft assembly	
		Segment Compressor 1&2
		Segment electric machine
		Segment compressor 3 and turbine
		Splined joint
	Diffuser	
	Bearing (5)	
	Non-sliding seal	
	Compressor 1	
		Stator stage 1
		Rotor stage 1
		Stator stage 2
		Rotor stage 2
		Stator stage 3
		Rotor stage 3
		Stator stage 4
		Rotor stage 4
		Stator stage 5
		Rotor stage 5
		Stator stage 6
		Rotor stage 6
		Stator stage 7
		Rotor stage 7
		Outlet volute
	Compressor 2	
		Stator stage 1
		Rotor stage 1
		Stator stage 2
		Rotor stage 2
		Stator stage 3
		Rotor stage 3
		Stator stage 4
		Rotor stage 4
		Stator stage 5
		Rotor stage 5
		Stator stage 6
		Rotor stage 6
		Stator stage 7
		Rotor stage 7
		Inlet volute
		Outlet volute
	Compressor 3	
		Stator stage 1
		Rotor stage 1
		Stator stage 2

		Rotor stage 2	
		Stator stage 3	
		Rotor stage 3	
		Stator stage 4	
		Rotor stage 4	
		Stator stage 5	
		Rotor stage 5	
		Stator stage 6	
		Rotor stage 6	
		Stator stage 7	
		Rotor stage 7	
		Stator stage 8	
		Rotor stage 8	
		Inlet volute	
		Outlet volute	
	Turbine		
		Stator stage 1	
		Rotor stage 1	
		Stator stage 2	
		Rotor stage 2	
		Stator stage 3	
		Rotor stage 3	
		Stator stage 4	
		Rotor stage 4	
		Stator stage 5	
		Rotor stage 5	
		Stator stage 6	
		Rotor stage 6	
		Stator stage 7	
		Rotor stage 7	
		Inlet volute	
	Electric machine		
		Stator	
			Reed Valce pack
			Winding
			HV connector
		Rotor	
			Shaft
			Permanent magnet
		Housing	
	Support flange (4)		
	Fixing screw (4)		
	Bearing lubrication jet		
	Components fixing screw (1)		

TABLE 3. TURBOCHARGER ASSEMBLY EBOM

Basement assembly

	Basement element	
	Cylinder block (4)	
		Cylinder
		Cylinder liner
	Head gasket (4)	
	Piston cooling jet (8)	
	Rear cover	
	Countershaft cover assembly (2)	
		Countershaft cover
		HV connector
		Gasket
		Fixing screw
		Bearing MDS Miba 26

TABLE 4. BASEMENT ASSEMBLY EBOM

Crankshaft

	Main Journal (5)
	Crankpin journal (4)
	Centering elements (6)
	Fixing screw (2)
	Auxiliar nose

TABLE 5. CRANKSHAFT EBOM

5.2 Cylinder Head assembly

The first element that has been analysed was the cylinder head assembly. Obviously, not all the components present in the Bill of Material have been analysed, for instance, the valve commands typically are produced by a third part and then are assembled with the head. Moreover, if the research would be deepened at this level it would be necessary far more time and resources.

Nevertheless, the main and the expected to be the more important, under economical point of view, components have been studied and modelled. This standard procedure has been exploited also for the turbocharger and basement assembly.

During this paragraph cylinder head element and its fixed elements – i.e. valve seat and guide – will be analysed and final evaluated costs have been pointed out.

The cylinder head element is one of the components that represents the “core” of a thermal engine, indeed, firstly, it has the task of composing, with the liner, the combustion chamber. It closes the cylinder liner and with its fire plate design determines the space inside the cylinder and the motion within. More, it holds the valves housing and guide, the ports into which flows the fresh mixture and the ones through which the exhaust gases are discharged. Moreover, in the upper part, it supports the camshaft and the distribution in general, allowing the flow of lubricant oil and, also, holding the coolant passages. The functions requested to the head suggests that a number of different kind of stresses must be overcame. The more important one involves the pressure produced by the gases, a very important fatigue load, another fatigue strain is due to the distribution dynamic load. Then, two static loads are present because of tightening of the screw that fixed the head with the cylinder block and due to the interferences of valves with guides and housings. A last stress comes, instead, from the thermal solicitation caused by the high temperature followed to the combustion process. [34]

Known these premises, it appears clear how much is important to wisely choose the material that makes up the head and which kind of design constraints must be observed. The base of this assembly, the cylinder head element, has designed to be casted exploiting a particular process named investment cast, or lost foam cast, the material chosen was a stainless steel, 17-4PH, that will be described better in the next chapter. For what concerns with the fixed elements, the mounting procedure on the head has been analysed and the machining after the installation has been studied.

The investment cast process is a cast that derives from the ancient lost foam invented more than 4000 years ago for the art production object. Basically, the idea is to exploit a wax model equals to the desired final metallic component. The procedure can be divided in some phases, among all, the greater benefit of this cast type is the very good tolerance that can be reached on the final piece, the final rugosity can achieve the range between 1.5-3 µm. Moreover, its costs are far lower with respect a die casting that in turn gives results also better than this but with a non-comparable economical expenditure. [24]

PROCESS	RUGOSITY R_A [MM·10^3]
DIE CASTING	0.5-3
INVESTMENT CASTING	1.5-3
CENTRIFUGAL PERMANENT MOULD CASTING	0.5-7.5
SAND CASTING	14-23

TABLE 6. TYPICAL RUGOSITY VALUE FOR CASTING PROCESSES

For what deals with the process, it can be said that the phases that make up the investment casting can be resumed with an image – Figure 30:

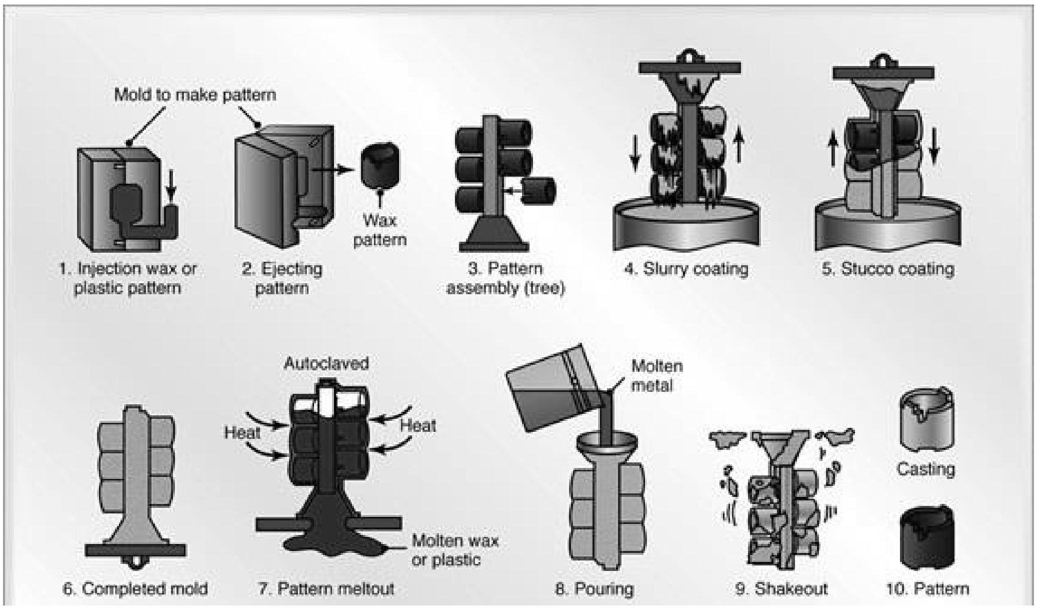


FIGURE 30. INVESTEMEN CASTING PHASES
SOURCE: HTTPS://ENGINEERINGPRODUCTDESIGN.COM/KNOWLEDGE-BASE/INVESTMENT-CASTING/

To be more precise, the investment casting process starts before the point (1), indeed, a first mould for the wax model production is needed. That metallic mold is usually made by aluminum alloy or steel and it is produced starting from CAD design exploiting a CNC machine; to do this work, different specialized companies exist around the world and it is a proper external step since it requires a special effort. Moreover, a mould designed for this purpose can last for a very high number of wax injection.

The proper process starts with the (1) wax injection, to perform this first step, typically, a wax injector machine is exploited, this is a sort of wax pump that works normally under vacuum to avoid inclusion of undesired product inside the paraffin model.

After (2) the extraction of the patterns from the machine, (3) the third step can go: during this phase the so called "bunch" is assembled, this term represents the union of several patterns in a same component. This action is justified since more models can be processed in a same operation. The various wax features are linked together through a central channel that in a successive step allows to pour the melt metal. This operation is practically totally manual, and it must be done by a team of workers that will need a laboratory working bench equipped with a smaller injection machine that can provide the right amount of wax mixed with a glue compound. The number of models that can be grouped in a same bunch is floating, in the sense that it depends on various aspects such the desired final accuracy, the budget available, the cast process time to be respected and so on.

FIGURE 31. WAX BUNCH EXAMPLE
SOURCE: HTTPS://ENGINEERINGPRODUCTDESIGN.COM/KNOWLEDGE-BASE/HOW-INVESTMENT-CASTING-WORKS/

Reached this point, (4) the ceramic shell that will be used for the metal production is manufactured. The shell is yielded in two different stages, in the first one a refractory mix is applied to the wax bunch, this compound is made up of very fine silica and some other type of binder. Across this pass is important that the slurry is very fine in order to ensure the desired level of accuracy under tolerance point of view. (5) The second stage, instead, aims of reinforcing the ceramic mould, to support and overcome the very high temperatures of the melted metal. The second material applied to the mold is composed mainly by sand and other less fine refractory aggregate and it is normally named stucco coating. The final thickness of the shell is typically around 15-20 mm.

After (7) the drying of the ceramic shell, the subsequent step is the wax melt out, this process involves the evacuation of the expendable wax model – for this reason this casting type is also known as lost wax casting – this step is particularly sensitive since it is important that no wax remains inside the ceramic shell, otherwise an inclusion could be detrimental for the metal melting and, in some cases, fatal for the cast process. For that reason, some particular material like the Titanium alloy, that are highly reactive, must exploit, not only an oven to melt out the wax but also an autoclave is needed in order to ensure that all the paraffins are melted out.

The sequent phase (8) is the pouring of the melted metal, during this step it is important the melting bakery chosen, in case of material different from basic steel; whenever a possibility of reaction with air is contemplated, an under vacuum furnace is suggested. This is the case of the cylinder head – and of the materials that are planned for the turbocharger stators and rotors. When the metal is melted, it is poured into the ceramic shell, the refractory mold is intelligently pre-heated in order to maintain for longer time the metal in melted condition, allowing increased dimensional accuracy.

Then, (9) the refractory shell must be shake-out, for this step, two stages are performed. The first step involves the destruction of the ceramic compound, this process is allowed thanks to a mechanical vibration machine. The severe vibration motion destroys the mold and allows to see for the first time the final metallic components.

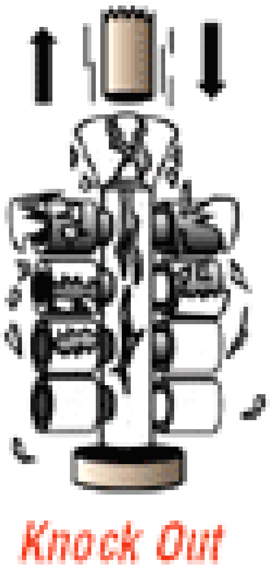


FIGURE 32. SHAKEOUT PROCESS

The second stage, instead, deals with the removal of remaining ceramic compounds adhered to the metal. To do this it is necessary the usage of a sand blasting machine, this device exploits the force of sand shot under pressure towards the component, that action allows to remove the remaining residual of the shell and in turn gives the metal bunch, ready to be cut and grinded.

The last step is, obviously, the cutting and grinding of the various components that make up the bunch. [24][25][26][27][28]

Strictly talking about cylinder head element investment cast process, it must be highlighted that the wax model is divided in five different patterns in order to reproduce the final design. This means that in the bunch production workstation an additional operation must be annexed, indeed the five patterns must be joined together and, only after that step, the model can be coupled with the bunch.

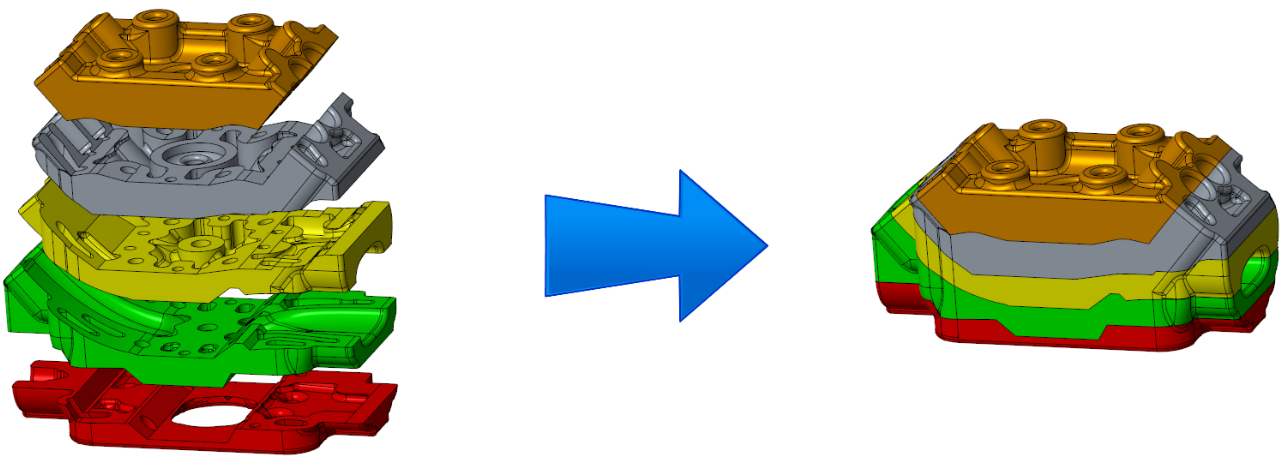


FIGURE 33. THE FIVE PATTERNS THAT MAKE UP THE HEAD
SOURCE: DE VIRGILIO M.R., "DESIGN AND FE ANALYSIS OF A CYLINDER HEAD FOR HIGH BMEP ICE FOR RANGE EXTENDER APPLICATION", TORINO, 2017

After the investment casting process, the component is firstly subjected to a heat treatment procedure and, afterwards, it is machined in a CNC working center. In the next paragraph the investment casting and the machining cycle will be explained deeper.

5.2.1 Weight and Cost Material

The material chosen is the stainless Steel 17-4 Ph, it is a martensitic precipitation-hardening steel. Martensite is a very hard, likewise brittle, metastable crystalline structure; it can be formed through a particular heat treatment that involves the usage of a rapid cooling of the melted metal. The process, known as quenching, is performed by the exploitation of oil or water as coolant.

At crystallographic level, this procedure results in body-centered tetragonal structure, supersaturated in carbon. In particular, the rapid cooling does not allow the iron **γ** phase – known as Austenite – to form the softer and less strong cementite compound, that is the structure that characterizes the steel material at low temperatures.

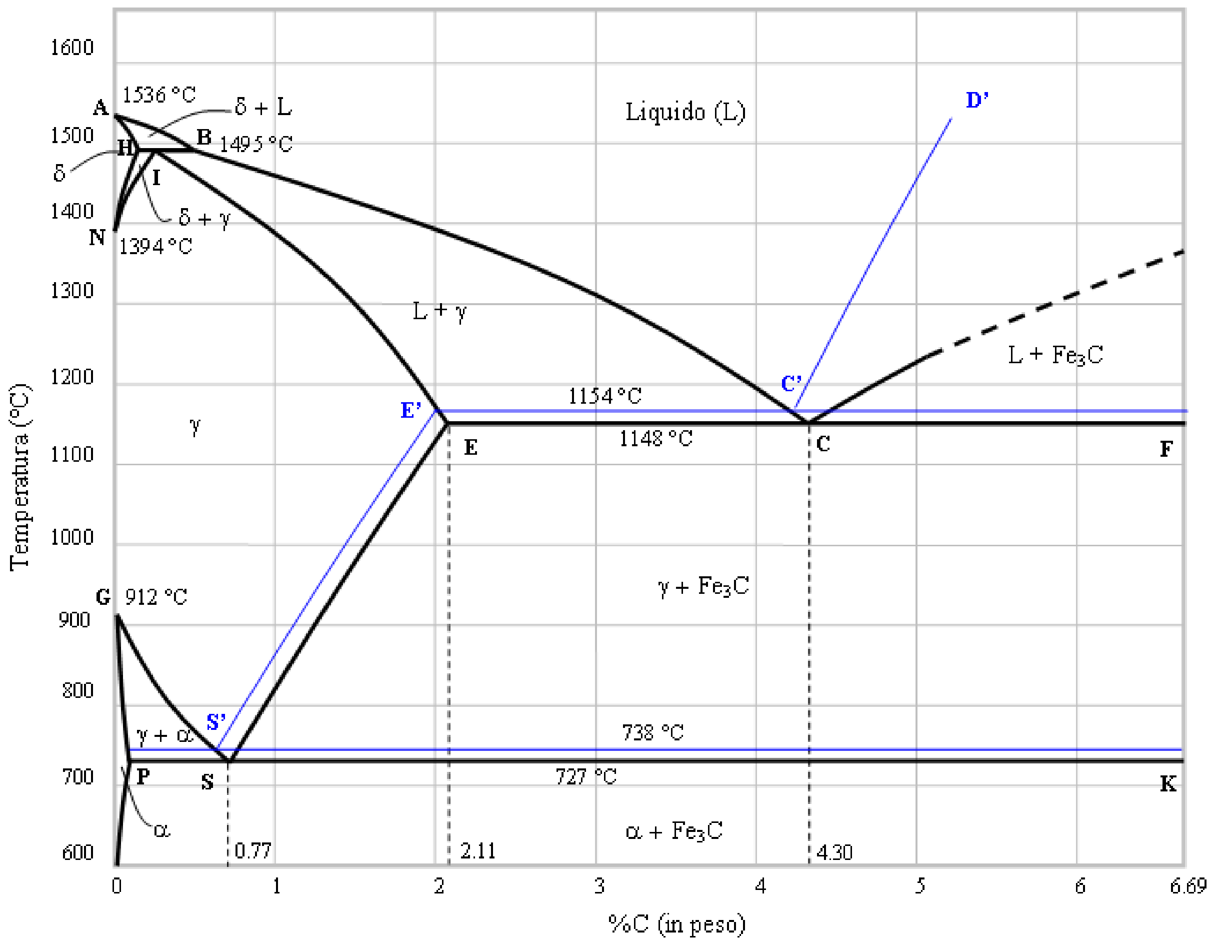


FIGURE 34. IRON-CARBON DIAGRAM
SOURCE: HTTPS://IT.WIKIPEDIA.ORG/WIKI/DIAGRAMMA_FERRO-CARBONIO

For what concerns the precipitation process, it includes a first solubilization step, the quenching phase – already explained above – and an aging.

1) The solubilization phase allows to add to the original steel an oversaturated quantity of elements like Chrome, Nickel, Copper thanks to the exploitation of high temperature. The solubility of such compounds inside the original steel composition is far increased thanks to high temperature.
2) The quenching phase as well as plays an important role in martensite formation, it also has the task of avoid the eviction of Chrome, Nickel and Copper. The rapid cooling, indeed, traps the

oversaturated alloy's components inside the solidified solution, this turns into an occupation of the dislocation, further improving the steel hardness. Moreover, since the included elements has some important peculiarities for what concerns corrosion resistance, the material is improved also under this point of view.

3) The last phase is the aging, it is the longest step since the steel has to be heated at a temperature lower than the **γ** transition one and the quoted temperature is then kept for a quite long time depending on the dimensions of the components. This phase is required in order to permit precipitation to take place.

The final result is a very hard structure that can overcome high working temperature and severe corrosion condition.

In the work performed in 2017 by Eng. De Virgilio, also a Titanium alloy had been considered, however, since the calculated performance was quite similar to the 17-4 Ph steel, the choice relapsed to the latter: Stainless-steel costs are far lower with respect to a Titanium alloy one.

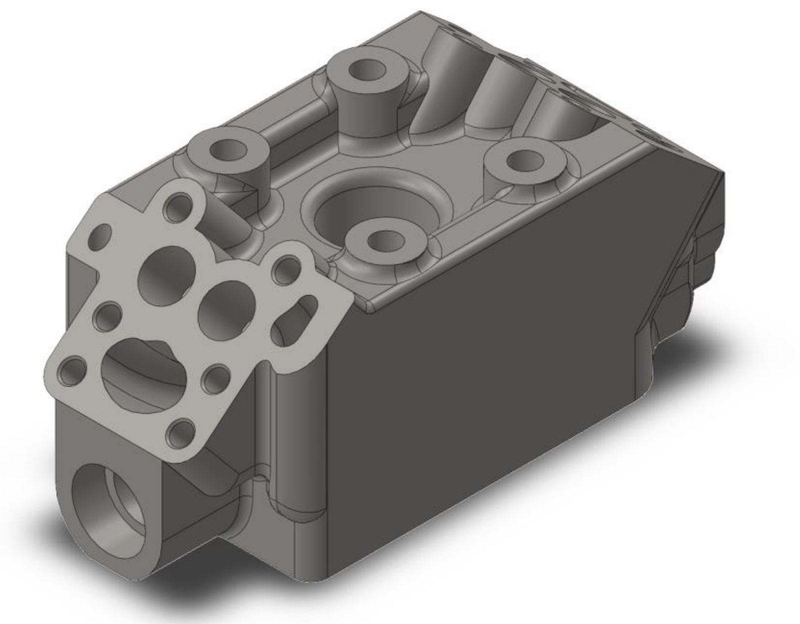


FIGURE 35. CYLINDER HEAD, FINAL DESIGN

For what deals with valve seats and guides, a steel vanadis 23 is the chosen material, is a high alloyed powder metallurgical high-speed steel. It is a material widely used for this type of application, since it ensures high wear resistance and compression strength. Moreover, it shows high machinability and temperature and corrosion tolerance.

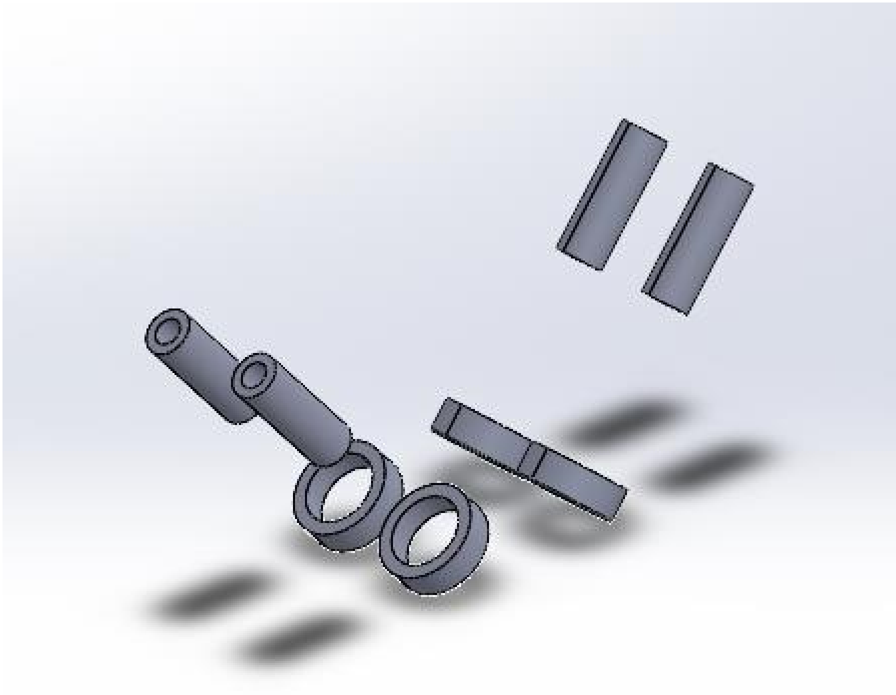


FIGURE 36. VALVE GUIDES AND SEATS

Knowing the material used is a very important task, in particular, the heat treatments necessary influence the cost analysis procedure and production planning choice. However, since the materials have been analyzed, the next step forward concerns with the evaluation of the under investigation components weights.

Starting from the CAD design, it has been possible to evaluate, firstly, the volumes of each component, then, known the materials and so the density of the pieces, the weights can be calculated.

Component	Material	Weight [g]	Volume [mm^3]	Density [Kg/m^3]	Quantity
Cylinder head element	Steel 17-4 PH	3116,47	399546,8	7800,0	4
Intake valve seat	Steel Vanadis 23	3,04	383,34	7940,0	8
Exhaust valve seat	Steel Vanadis 23	3,04	383,34	7940,0	8
Valve guide	Steel Vanadis 23	4,12	518,36	7940,0	16

TABLE 7. CYLINDER HEAD WITH FIXED ELEMENTS WEIGHT

Once the net weights are defined, it is necessary to evaluate the overall amount of material that is needed for the component's production.

The process, indeed, is characterized by some losses and parameters that must be taken into account, the total amount of material requested for the casting is starting to be calculated from the net weight defined above, nevertheless other aspects play a role:

- Scrap Rate **SR**: a part of the melted metal is simply wasted during all the process; in other worlds, the metal that is transformed into gates, runners and risers is put under this voice, moreover, metal lost from the ladle and casting scrap are considered too. To account for this aspect, a percentage is taken into account.
- Yield of the process **Y**: under this name is considered the defective percentage that the process gives in return. A less defective amount of component turns into a high yield of the process that results in a less quantity of metal requested for the casting.
- Melt loss **ML**: This parameter accounts for the quantity of metal that, during the fusion process, is contaminated – for instance, due to an oxidation phenomenon – that cannot be recycled and so that cannot be considered as scrap.
- Finishing and cleaning scrap rate **FSR**: this voice evaluates the machining allowances and also all the value that deals with the cutting and finishing of the model that are separated from the bunch. [33][22]

With the meaning of these parameters clear in mind, it is possible to calculate the amount of material needed for the production of each component:

$$TWP = CW \cdot \frac{1}{1-SR} \cdot \frac{1}{Y} \cdot \frac{1}{1-ML} \cdot \frac{1}{1-FSR} \tag{9}$$

With TWP it is intended the total weight of material needed per piece and CW equals to the net weight of the component.

Reached this point, the value of each coefficient has been calculated and, in particular, for the investment casting process the following values have been assessed:

Coefficient	Description	Value	Unit
CW	Casting Weight	3,12	kg
SR	Scrap Rate for investment casting	5	%
Y	Yield	75	%
ML	Melt loss	6	%
FSR	Finishing and cleaning scrap rate	2	%

TABLE 8. INVESTMENT CASTING COEFFICIENT VALUE

Known the values, it is possible to evaluate the kilograms of material needed in order to produce a single cylinder head, applying the equation (9) and consider the value in Table 8, **4.75 Kg** is necessary for the production of each cylinder head.

Before calculating the steel cost for a cylinder head, the amount of wax requested for the initial foam pattern must be assessed, the value has been found starting from the head volume – reported in Table 7 – and multiplying it with the wax density. This second value has been considered equals to 1130 kg/m^3 and the final value of wax necessary for each component has been evaluated in **0.45 Kg.**

Reached this point, the work has only requested to find a price per kilogram for both steel and wax, and to multiply the amount of material needed and the price per kilogram – the equation (10) translates this procedure in number. However, another point must be taken into account, since scrap produced during casting process can be recycled, a 25% of must be subtracted to the final voice related to the steel cost.

(10) $$Cost/head = Cost/kg \cdot kg$$

The actual price per kg assigned for the material considered are reported here:

MATERIAL	COST/KG [€]
STEEL 17-4PH	6
PARAFFIN	1.1

TABLE 9. MATERIAL COST PER KILOGRAM
SOURCE: HTTPS://WWW.LME.COM/METALS/FERROUS

Last, the cost the material needed for the ceramic shell, known the dimension of each bunch, has been estimated in 87.5 €/bunch, that, considering that each bunch is composed by 20-cylinder heads model – in the next paragraph the bunch dimensioning will be explained – results in 3.5 €/head.

Considering all the previous explanation the final cost for the materials necessary for one cylinder head production are reported below:

	€/head with fixed element	
Material	Steel 17-4 ph	€ 21,39
	Wax	€ 0,54
	Ceramic shell material	€ 3,50

TABLE 10. CYLINDER HEAD COST FOR MATERIALS

5.2.2 Manufacturing Processes and Related Costs

After the materials cost computation, the manufacturing process have been studied in order to point out the industrial equipment that must be purchased and the size and kind of the staff that is requested for the production.

In the first part of this paragraph, the casting process has been considered; in the second part, instead, the machining procedure have been analysed. The last part is dedicated to the valve guide and seat planting and their respective re-working procedure.

The starting data for the investment casting procedure was the target number of components that must be produced per year – considering that the cylinder heads for each engine are four, the target production is represented by 80000 cylinder head per year – and the step necessary for the investment casting described in paragraph 5.1.1.

Going more in deep, to understand the kind and the number of machineries needed, the different production areas have been individuated and the time and number of items processed together, in each of this zone, have been evaluated.

Considering that the mould production for wax injection is an extraordinary expense since this kind of mould lasts for a very high number of injections, the first area designed aims of producing wax bunches. This *first area* is equipped with a MPI 35 series 4 post wax injector, as it is suggested by the name, it is a wax injection machine that ensures 0.28 kg of wax injected per second, considering that the mould is thought with the patterns that guarantees the production of 5 figures, the time for the injection can be evaluated– since the wax weight of a single model and the mass flow of the machine are known – in 8.13 s for five models.

FIGURE 37. MPI 35 SERIES 4 POST INJECTION MACHINE

Then, 120 s is calculated for the discharge of the five wax models and for inserting again the mould inside the machine. To govern the machine and handle the models a specialized operator is foreseen.

The last phase in this area involves the assembly of the bunch, this procedure must be performed totally manually and deals with the bounding of the five parts that make up a wax model and the successively gluing of the model to the bunch. To reach a value of 300 s for a bunch production, four operators endowed with a wax injector and a working table are needed.

The times for the bunch wax production are here reported:

BUNCH WAX PRODUCTION

MOULD FILLING	8,13	s/5 models
SETUP TIME	120	s/5 models
FIVE WAX MODELS PRODUCTION	128,13	s/5 models
BUNCH ASSEMBLY	300	s/bunch
TOTAL	812,51	s/bunch
OVERALL TIME FOR SINGLE HEAD	40,63	s/model

TABLE 11. BUNCH WAX PRODUCTION TIMING

Once this first area has been designed, the cost expected have been evaluated. Starting from the labour cost, it has been considered workers' wages equal to 23000 € for the specialised operator that uses the wax injection machine and 20000 € for each worker that composes the bunch assembly crew.

To these expenses, the machinery and tools costs have been assessed coupled with their relative maintenance and energy consumption. As it has previously introduced, a machinery depreciation per year of 25% have been calculated, a portion equals to 7% of investment cost have been taken into account for the maintenance and 0.155 €/kWh have been considered for the electricity cost.

Then the year expenses have been divided for the available hour of work – 3840h – in order to find the hourly cost of the cost centre analysed. However, at this point, an important consideration must be done, indeed, since during a year some times must be dedicated to the machine maintenance or also failure must be considered, the productive time does not correspond with 3840 h. This amount of time is modelled as 15% of the overall working time per year resulting in 3264 h. This fact affects the workers hourly cost that will be divided for 3264h, since it is the real productive time, the labourer must be paid also during maintenance periods increasing the hourly cost centre.

Before presenting the hourly cost of this first department, the investment dedicated to the machine and tools of this area considered have been reported:

- 140 000 € is the cost associated with the MPI 35 series machine that turns into 35 000€ of depreciation per year. Its electric consumption is equal to 12 kWh that, considering an electric motor efficiency of 85%, increases to 14,4 kWh. The maintenance amounts to 9800 € per year.
- Glue injector costs 3000 € resulting in 750€ of depreciation per year. Its maintenance corresponds to 120 €/year.

- Wax injector machine cost is 60 000 € equals to 15 000 € of depreciation. Its maintenance amounts to 4200 €/year.

Considering these values, the cost per hour is evaluated in **80.14 €/h**.

As *second cost centre*, the ceramic shell production and dewaxing area has been designed. Here, the wax bunch produced before has been exploited to produce the ceramic mould and, then, it is evacuated during the dewaxing phase. Basically, for this department, two industrial furnaces are needed to dewax the ceramic shell and to bake the shell itself. However, before that procedure, the ceramic slurry and the stucco coating must be applied to the wax bunch. For that step, an automated robot is used to move the wax bunch inside the slurry mix and stucco, then an ambient dehumidifier is adopted to fix the refractory material to the wax bunch.

For what deals with the times spent in this area, it must be highlighted that the times foreseen inside the furnaces must be divided for the bunches baked together, for instance, the drying phase lasts 2 hours however, since 25 bunches are dried together, the amount time for each bunch is 288 s.

The time needed for the application of refractory material is evaluated in 2 minutes, for dewaxing phase and ceramic shell baking 20 minutes are needed for both. To those values, 300 s per bunch are estimated for the setup time and for the handling of the bunches.

Therefore, the times evaluated are reported here:

CERAMIC SHELL PRODUCTION AND DEWAXING

REFRACTORY SHELL APPLICATION	120,00	s/bunch
DRYING TIME	288,00	s/bunch
DEWAXING TIME	48,00	s/bunch
SHELL BAKING TIME	48,00	s/bunch
SETUP AND HANDLING TIME	300,00	s/bunch
TOTAL	804,00	s/bunch
OVERALL TIME FOR SINGLE HEAD	40,20	s/model

TABLE 12. CERAMIC SHELL PRODUCTION AND DEWAXING TIMES

Before presenting the equipment for this department, a bracket must be opened for the number of bunches handled together in the furnaces. Indeed, in order to avoid the creation of bottleneck, the overall time in each department must be equal to the time of other areas. This allow that the machines are well saturated, no money are wasted in machines over dimensioned; moreover, also the payment of workers is motivated and, theoretical, no dead time is experienced. Therefore, the furnaces have been chosen in order to bake 25 bunches per time, allowing to align the time of this department with the one of the bunch productions. Moreover, the 40 s reached for each area are constrained by the total amount of engine produced per year, in other worlds, it is the time necessary to satisfy the year production target. Obviously, this study have been included a check with the furnaces' capacity, so a bunch dimensioning and designing phase have been part of the analysis; the final solution compatible with both capacity and timing adopted is reported here:

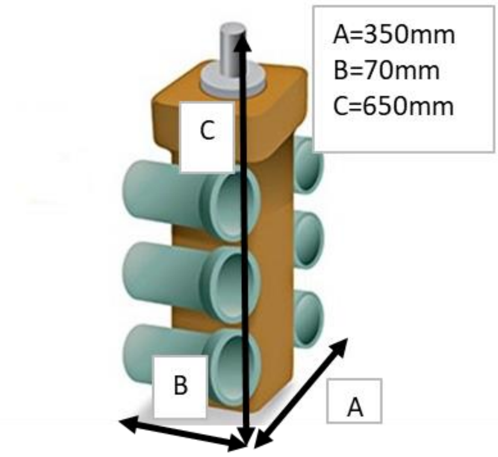


FIGURE 38. BUNCH DESIGN AND DIMENSIONS

For what deals with this cost centre, four ordinary workers are paid 20 000€ per year, and a specialised operator is foreseen for the supervision of the automated robot and he is paid 23 000 € per year. The four labourers are divided one for each furnace and the remaining two are devoted to handle the bunches between the furnace and the drying area.

For what concerns with the equipment of this area, the robot chosen is a 7-axis degree of freedom Kawasaki BX100LFE02001, its purpose is to merge the wax bunch inside the centrifugal ceramic mixer and then move the bunch in the drying zone. The ceramic mixture is manufactured by PKI and it is the SM-18 model.

FIGURE 39. PKI SM-18 MIXER

The dryer is provided by OMI Italy, in particular, the ED660 230/1/50 model have been chosen.

FIGURE 40. OMI ED660 230/1/50 DEHUMIDIFIER

Last, the furnaces will be given by LM industry, the model chosen it is the LT1.68E, dimensions and model is shared between the dewaxing procedure and ceramic shell baking; however, the first one has less heating power with respect to the second, indeed, a maximum temperature of 500 ° has guaranteed. The ceramic shell oven, instead, since higher temperatures are requested, ensures a maximum temperature of 1200°.

The investment cost of all the equipment and its handling is reported below:

- Kawasaki's robot costs 75 000 € equals to 18 750 € of depreciation per year, its consumption is quantified 4.3 kWh and its maintenance is 3000 € per year.
- PKI's centrifugal mixer costs 50 000 € equals to 12 500 € of depreciation per year, its consumption is 2.2 kWh.
- OMI's dryer costs 10 000 € equals to 2500 € of depreciation per year, its consumption is 1.364 kWh and its maintenance is 400 € per year.
- LM's 500° furnace costs 60 000 € equals to 15 000 € of depreciation per year, its consumption is 36 kWh and its maintenance is 2400 € per year.
- LM's 1200° furnace costs 100 000 € equals to 25 000 € of depreciation per year, its consumption is 96 kWh and its maintenance is 4000 € per year.

Considering these values, the cost per hour is evaluated in **105.85 €/h**.

The *third cost centre* is devoted to the melting of the steel, its pouring and the subsequent shakeout of the shell. Moreover, also the cutting and grinding of the models from the bunch is performed here.

For the metal melting is used, as it is previously introduced, a furnace under vacuum that ensures a good fusion minimising the risk of inclusion inside the final product. The time for the melting process and for the pouring is evaluated considering the melted material flow of the furnace that corresponds to 1800 kg per hour and using the value of the amount of material needed for a single bunch.

The vibrational shakeout phase is calculated to last one minute, while for the sanding blasting process, it must be considered that, as for the furnaces of second department, 25 bunches are processed together, and so the hour needed for sand blasting treatment must be divided for 25, resulting in 144 s/bunch.

FIGURE 41. SHAKEOUT VIBRATION MACHINE

At last, for the cutting and grinding procedure 20 s per bunch have been computed.

FIGURE 42. GRIT GX75 GRINDING MACHINE

The overall time spent in this department is reported below, together with each step duration:

METAL POURING, CUTTING AND GRINDING

MELTING AND POURING TIME	190,14	s/grappolo
VIBRATIONAL SHAKEOUT	60	s/grappolo
SAND BLASTING	144	s/grappolo
CUTTING AND GRINDING	20	s/grappolo
OVERALL	794,14	s
OVERALL TIME FOR HEAD	39,71	s

TABLE 13.MELTING, CUTTING AND GRINDING TIMES

The labor crew is composed by two operators for the handling of under vacuum furnace, other twos are assigned to the shakeout machines. For the cutting and grinding department 3 operators are foreseen.

The investment cost of all the equipment and its handling is reported below:

- STVF-Q-160's under vacuum furnace costs 400 000 € equals to 100 000 € of depreciation per year, its consumption is quantified 160 kWh and its maintenance is 20 000 € per year.
- GKF's vibrational shakeout machine model 07 costs 100 000 € equals to 25 000 € of depreciation per year, its consumption is 16.5 kWh and its maintenance is 7 000 € per year.
- RVH69's auto blasting machine costs 200 000 € equals to 50 000 € of depreciation per year, its consumption is 72.6 kWh and its maintenance is 14 000 € per year.
- Bekamak's band saw model BMSO-420-XS costs 50 000 € equals to 12 500 € of depreciation per year, its consumption is 18 kWh and its maintenance is 3500 € per year. At this voice also 4000€ per year must be considered for the blade substitution
- GRIT's grinding machine model GX75 costs 1500€ equals to 375 € of depreciation per year.

Considering these values, the cost per hour is evaluated in **196.60 €/h**.

The *last area* dedicated to the casting process is the one thought for the heat treatments. In this case, the area is composed by two equal furnaces, this needed is justified by the different times for solubilization treatment and for the hardening one. The two furnaces are the same chosen for the ceramic shell bake, and, specifically, they are two LM LT1.68E-1200° ovens.

FIGURE 43. LM LT1.68E-1200° FURNACE

The times foreseen for the two step of the steel 17-4PH heat treatments are respectively 30 mins and 4 hours for solubilization and hardening, also in this case, these times must be divided for the models processed together, in that case it is talked about models since the cutting procedure is already overcame. The choice of the number of models processed together have followed the same path of the choice performed before in ceramic shell department. The overall time had to be in line with the timing of other departments, resulting in the baking of 400 heads per time. This number is obviously allowed by the 1.68 m^3 of space inside the LM furnaces chosen.

Below the table of the times is reported:

HEAT TREATMENT

SOLUBILIZATION	4,5	s/model
HARDENING	36	s/model
OVERALL	40,5	s/model
	0,7	min/model
OVERALL TIME FOR HEAD	40,50	s/model

TABLE 14. HEAT TREATMENT DEPARTMENT TIMES

For this department, only one worker is needed to handle the furnaces, the wage is 20 000 € per year.

For what concerns with the furnaces the investments are here reported:

- LM's 1200° furnace costs 100 000 € equals to 25 000 € of depreciation per year, its consumption is 48 kWh and its maintenance is 4000 € per year.
- LM's 1200° furnace costs 100 000 € equals to 25 000 € of depreciation per year, its consumption is 48 kWh and its maintenance is 4000 € per year.

Considering these values, the cost per hour is evaluated in **41.76 €/h**.

The casting procedure designed for the cylinder head has been presented now, and a resume of the timing and of the costs of each cost centre is here provided.

FIGURE 44. TIMES FOR EACH PRODUCTION AREA

Considering the value founded in the research, the production foreseen for a year is of 85 846, that is a satisfying value considering the 80 000 heads per year target production.

$T_{tot,casting\ single\ head}$	**161,03**	s
	2,68	min
Head Produced/year	85846,12	

TABLE 15.OVERALL TIMING FOR EACH HEAD AND PRODUCTION/YEAR

Since the heads produced in an hour by the casting line are 21, the cost for the production of a single head that comes from each cost centre can be evaluated.

	€/head with fixed element	
Cost Center	Wax bunch prod.	€ 3,82
	Ceramic shell prod. and dewaxing	€ 5,04
	Melting and shell removal	€ 6,97
	Cutting and grinding	€ 2,39
	Heat treatments	€ 1,99

TABLE 16. CASTING COST CENTRE EXPENSES FOR A SINGLE HEAD

The last part of the cylinder head cost analysis involves the evaluation of the *machining working cycle* and the consequent costs that derives from it. In particular, the cycle design helps to understand the time needed for the machining procedure, and, more important, the number of machines and tools necessary for the target production.

The working cycle is a document, divided in phase, that has the aim of representing the different machining process that must be performed on the component in order to get the final piece. Moreover, it shows all the cutting parameters, the time for each operation and all the component positioning for each transformation. It is a very useful tool in order to understand the timing and the costs related to tools.

It is subdivided in phases and subphases, the firsts group all the operation that are performed on the same machine and in the same position, the seconds, instead, group all the operation done in the same machine and with the same positioning. Since in that case all the operations have been design to be made in the same CNC machine, the phases represent the operations performed in the same positioning, while the subphases are the operations done with the same tool.

After these premises, the specific cycle of the cylinder head can be explained. However, before presenting the working procedure designed, the CNC working centre is introduced, indeed, for studying and analyzing the cycle, the available space for the working area inside the machine must be considered. This aspect is of particular interest in the case of the cylinder head: this is justified because a high number of phases have been necessary during the transformation design; therefore, the time needed for a single cylinder head is quite high, and, in order to minimize that value – sharing the setup time between more models –, more than one head have been thought to be worked together. Moreover, since during the transformation, more than one positioning have been needed, two type of schemes have been designed.

The machining plate available for the working procedure is of circular type, the two plates designed for the fixing of the heads during the operations are rectangular considering the same shape of the projected area of the components. Below, the two positionings are reported, the black lines represent the machine working area, the blue lines, instead, are the scheme of the plate and models mounted on it.

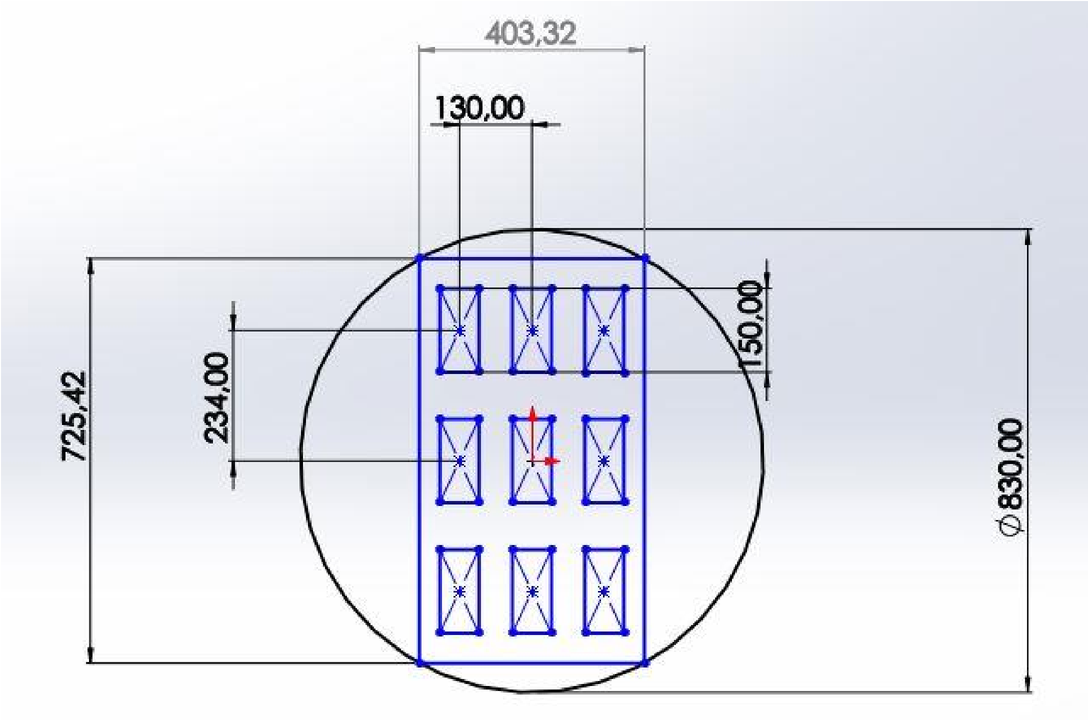


FIGURE 45. CYLINDER HEAD MACHINING, POSITIONING 1

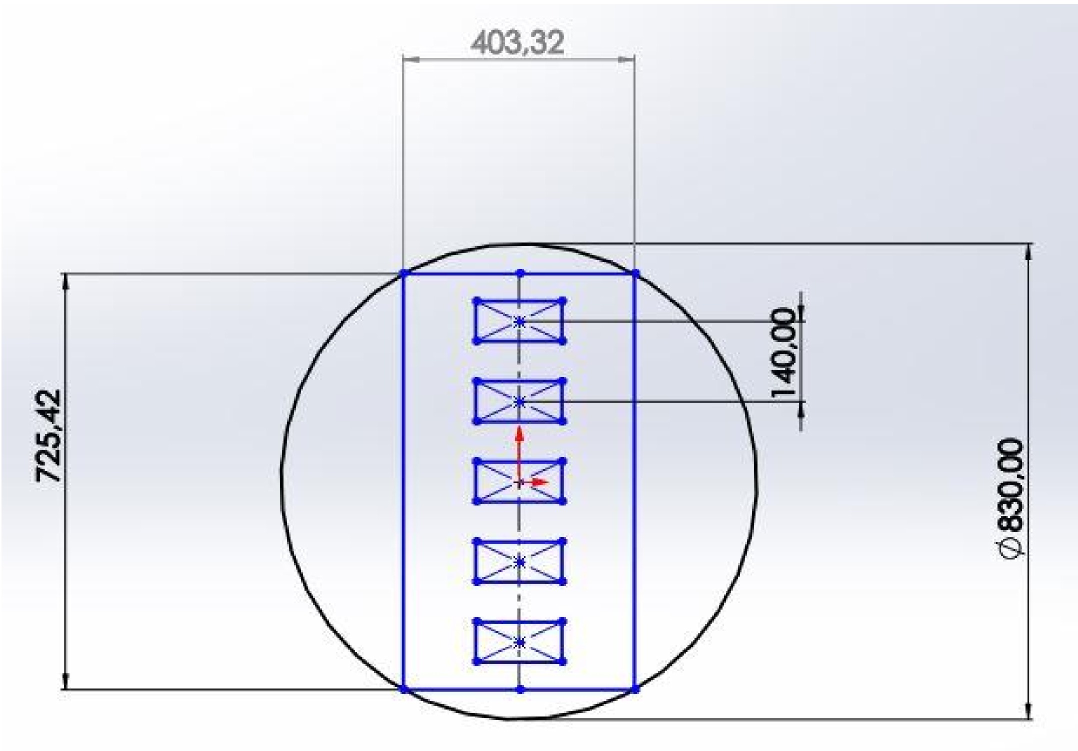


FIGURE 46. CYLINDER HEAD MACHINING, POSITIONING 2

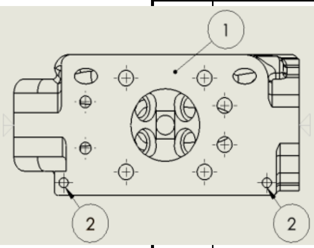
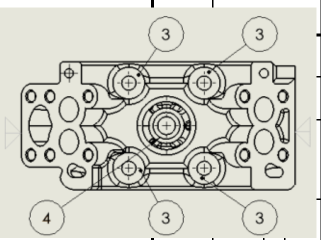
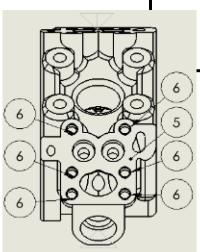
The working area represented above corresponds to the one of the chosen CNC machine that is a vertical 5 axis CNC machine produced by Okuma. It is the model MU-6300V.

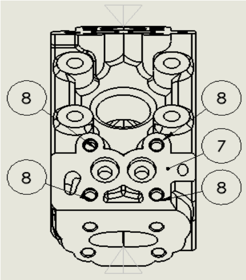
The tools and the tools carriers have been chosen from the Seco Tools catalogue and, obviously, the cost estimation have been performed considering the prices indicated by the same company. Moreover, the duration, the cutting parameters have been provided too by Seco.

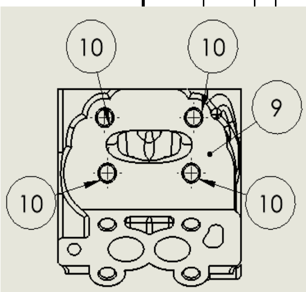
FIGURE 47. OKUMA MU-6300V

For what deals with the operations performed on the model, it can be said that two main general transformations have been needed: the milling of the surfaces in contact with other components – so the removing of the allowances coming from the casting procedure –, the drilling of the smallest duct that cannot be done with the casting process and the tapping of the holes where a bolt must be used.

In the next pages, the working cycle designed is reported.

N° ph	Sketch	Description	Cutting parameters								t		
			a	Vt	N	D	N°	f_t	N° p	p			
10		10.0 Plate mount.	-	-	-	-	-	-	-	-	600		
		10.1 Pos.1 centering	-	-	-	-	-	-	-	-	180		
		10.2 Milling 1											
		10.2.1 Roughing	0,76	100	397,89	80	8	0,24	1	1,7	9,08	x	9
		10.3 Tool change	-	-	-	-	-	-	-	-	1,8		1
		10.4 Drilling 2											
		10.4.1 Pre-drill	0,91	130	8276	5	-	0,11	1	15	0,071	x	18
		10.4.2 Tool change	-	-	-				-	-	1,8		1
		10.4.3 Drill	0,73	105	6684	5	-	0,11	1	47,19	0,088	x	18
		10.5 Pos.1	-	-	-	-	-	-	-	-	100		1
		10.6 Tool change	-	-	-	-	-	-	-	-	1,8		1
		10.7 Finishing	0,18	70	278,52	80	8	0,08	1	0,3	38,91	x	9
20		20.0 Plate mount.	-	-	-	-	-	-	-	-	600		
		20.1 Pos. 2 centering	-	-	-	-	-	-	-	-	180		1
		20.2 Tool change	-	-	-	-	-	-	-	-	1,8		1
		20.3 Milling 3											
		20.3.1 Roughing	0,22	70	1114	20	2	0,1	1	1,7	4,85	x	36
		20.4 Tool change	-	-	-				-	-	1,8		1
		20.5 Milling 4											
		20.5.1 Roughing	0,24	85	1691	16	3	0,048	1	1,7	0,88	x	9
		20.6 Pos 2. recentering	-	-	-	-	-	-	-	-	100		1
		20.7 Tool change	-	-	-	-	-	-	-	-	1,8		1
		20.8 Milling 3	0,081	80	2122	12	1	0,038	2	0,3	22,32	x	9
		20.9 Tool change	-	-	-	-	-	-	-	-	1,8		1
		20.10 Finishing	0,18	70	743	30	3	0,08	1	0,3	6,06	x	36
30		30.1 Rotation pos. 2 +50° x	-	-	-	-	-	-	-	-	180		0
		30.2 Tool change	-	-	-	-	-	-	-	-	1,8		1
		30.3 Milling 5											
		30.3.1 Roughing	0,73	100	505	63	6	0,24	1	1,7	5,77	x	9
		30.4 Tool change	-	-	-				-	-	1,8		1
		30.5 Tapping 6	0,05	39	1773	6	-	0,0026	1	22	4,77	x	54
		30.6 Pos.2 recentering	-	-	-	-	-	-	-	-	100		1
		30.7 Tool change	-	-	-	-	-	-	-	-	1,8		1





	30.8 Finishing	0,17	70	354	63	6	0,08	1	0,3	24,74	x 9
40	40.1 Rotation pos. 2 (20.1) - 100° asse x	-	-	-	-	-	-	-	-	180	0
	40.2 Tool change	-	-	-	-	-	-	-	-	1,8	1
	40.3 Milling 7										
	40.3.1 Roughing	0,36	100	505	32	3	0,12	1	1,7	11,73	x 9
	40.4 Tool change	-	-	-	-	-	-	-	-	1,8	
	40.5 Tapping 8	0,05	39	1773	6	-	0,0026	1	22	4,77	x 36
	40.6 Pos.2 recentering	-	-	-	-	-	-	-	-	100	1
	40.7 Tool change	-	-	-	-	-	-	-	-	1,8	1
	40.8 Finishing	0,17	70	696	32	3	0,08	1	0,3	25,13	x 9
50	50.0 Plate Mount.	-	-	-	-	-	-	-	-	600	
	50.1 Pos. 2 centering	-	-	-	-	-	-	-	-	180	1
	50.2 Tool change	-	-	-	-	-	-	-	-	1,8	1
	50.3 Milling 9										
	50.3.1 Roughing	0,76	100	637	50	5	0,24	1	1,7	5,26	x 5
	50.4 Tool change	-	-	-	-	-	-	-	-	1,8	1
	50.5 Tapping 10	0,05	39	1773	6	-	0,0026	1	22	4,77	x 20
	50.6 Pos. 2 recentering	-	-	-	-	-	-	-	-	100	1
	50.7 Tool change	-	-	-	-	-	-	-	-	1,8	1
	50.8 Finishing	0,18	70	446	50	5	0,08	1	0,3	22,56	x 5

TABLE 17. CYLINDER HEAD WORKING PROCEDURE

Here it is shown the working procedure of the cylinder head. Each operation is characterized by a preliminary roughing phase and it is followed by a successive finishing phase. About the notation of the table, it can be said that:

- a is the advancement of the tools
- V_t is the cutting velocity
- N is the RPM of the tool
- D is the diameter of the cutter
- N° is the number of teeth of the cutter
- f_t is the feed rate of the tool
- N° p is the number of pass
- P is the pass deep
- t is the time of the operation

Two notes must be reported, the first deals with the multiplicator on the right of the time column, this is the multiplicative factor due to multiple equal operations and due to the number of components to be worked on the same plate. The second comment is about the voice of subphase "Plate mount." The time relates to this operation is not accounted for since it is a manual preliminary operation that it is performed by a worker meanwhile the machine is performing a transformation on another plate.

At this point a total amount of time needed for the working of each head can be computed:

Tot.	**375,03**	**s**
	6,25	min
	0,10	h

TABLE 18. TIMES FOR A SINGLE HEAD MACHINING

Reached this point, before deciding the number of same working station to be used in parallel – in order to satisfy the target production –, the valve guides and seats mounting and machining must be evaluated too.

For the seats and guide installation a specific press must be used, moreover, to facilitate the mounting procedure, a small oven is used to dilatate the cylinder head hole and, at a same time, liquid nitrogen is exploited to restrict the seats and guides. After the mounting, a milling machine has been taken into account for the re-working of the two new fixed components.

Therefore, two phases have been added to the previous working cycle in order to evaluate in a proper way all the time needed for this second part of cylinder head production. For what deals with the positioning, in this case a new standard have been sketched since the mounting procedure have been thought to be performed on a different machine tool.

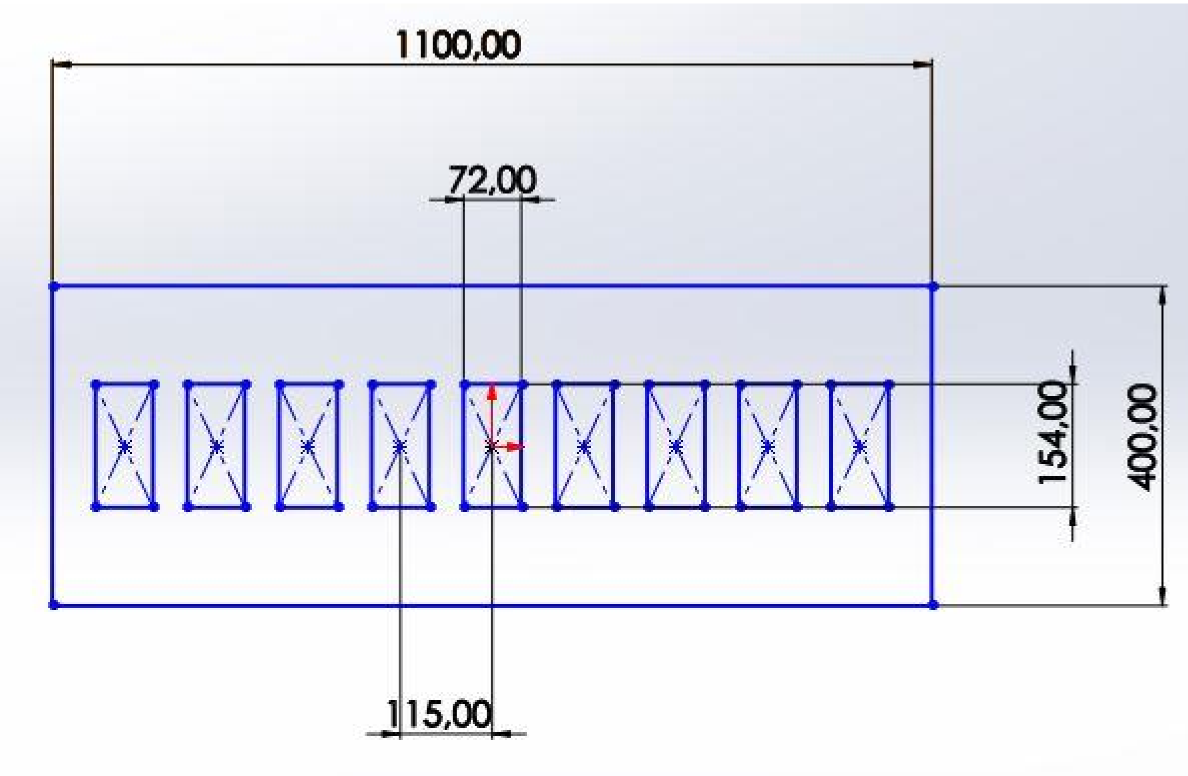


FIGURE 48. POSITIONING ON THE PRESS MACHINE TOOL

The machine chosen for the mounting is a specific press designed by Comec for this kind of application, the model is the BGV260.

FIGURE 49. VALVE GUIDE AND SEATS MOUNTING PRESS

The phases involved in this last step to the final product manufacture is reported below:

N° phase	Description	Cutting Parameters								t		
		a (*)	Vt	N	D	N°	f_t	N° p	p			
60	60.0 Pos.4 Mounting on Press	-	-	-	-	-	-	-	-	600		
	60.1 Pos. 4 centering	-	-	-	-	-	-	-	-	300		1
	60.2 Installation guide 11	-	-	-	-	-	-	-	-	3	x	36
	60.3 Tool change	-	-	-	-	-	-	-	-	1,8		1
	60.4 Installation valve 12	-	-	-	-	-	-	-	-	3	x	36
70	70.0 Plate mounting	-	-	-	-	-	-	-	-	600		
	70.1 Pos.1 centering	-	-	-	-	-	-	-	-	300		1
	70.2 Milling valve seat 12											
	70.2.1 Finishing	0,21	90	1910	15	1	0,11	1	0,8	4,22	x	36(*)

TABLE 19. VALVE SEATS AND GUIDES INTALLATION AND RE-WORKING

(*)The notation is the same adopted in the previous working cycle parts

The total amount of time computed for the seats and guide installation and re-working is here copied:

Tot $_{Valve}$	**20,27**	**s**
	0,34	min

TABLE 20. VALVE GUIDES AND SEATS INSTALLATION AND RE-WORKING TIME

At this point, summing up the two times contribution coming from the two-working procedure, it has been possible deciding how much working stations are needed to satisfy the desired yearly production. Considering the numbers founded and the long duration of such a high number of transformations, the final decision involves the usage of three working station in parallel for the cylinder head machining and two working station in parallel for the cylinder head with fixed element re-working procedure. In this way the 20 000 engine production target can be reached, but, obviously, this comes at expenses of cost that in such a configuration is respectively tripled and doubled.

To be more specific, the two different working stations are described, and their related costs are here specified:

Cylinder head machining:

- CNC machine Okuma MU6300V costs 300 000 € resulting in a depreciation per year equals to 75 000 € per year. Its consumption corresponds to 13.2 kWh and related maintenance is equal to 21 000 € per year.
- A qualified operator handles the CNC machine with a wage of 23 000 € per year
- Tool carriers' costs are equal to 5100 €
- Tools costs have been evaluated considered the prescribed Seco Tool duration of 30 mins. Starting from the cutting time evaluated in the working cycle, from the overall productive working hour and from the overall cycle duration, it has been possible to evaluate the overall tools consumption and costs quantified in 119 970 € per year.

Fixed Element Machining:

- Comec press BGV260 costs 10 000 € equals to a depreciation per year of 2500 €. Its consumption is equal to 1.8 kWh and its maintenance to 700 €.
- An operator is dedicated to the press with a wage of 20 000 € per year.
- Then liquid nitrogen (300L/year is the estimated consumption) and a dedicated reservoir (3L) from AirLiquide have been chosen for an expense of 4500 € per year
- A small industrial induction oven for the preheating of the head costs 15 000 € equals to 3750 € per year. Its consumption is considered 5.4 kWh.
- A milling CNC machine investment equals to 120 000 €, with a depreciation of 30 000 per year. With a consumption of 13.2 kWh and a maintenance foresees in 8400 €.
- A qualified operator handles the CNC machine with a wage of 23 000 € per year
- Tool carriers' costs amount to 300 €
- Tools costs have been evaluated in the same way used for the previous machining process and corresponds to 4830 € per year.

Considering all that voices, also the hourly cost for each of the two machining cost center can be evaluated:

	€/HEAD WITH FIXED ELEMENT	
COST CENTER	Machining	€ 10,52
	Valve seat and guide installation and machining	€ 4,16

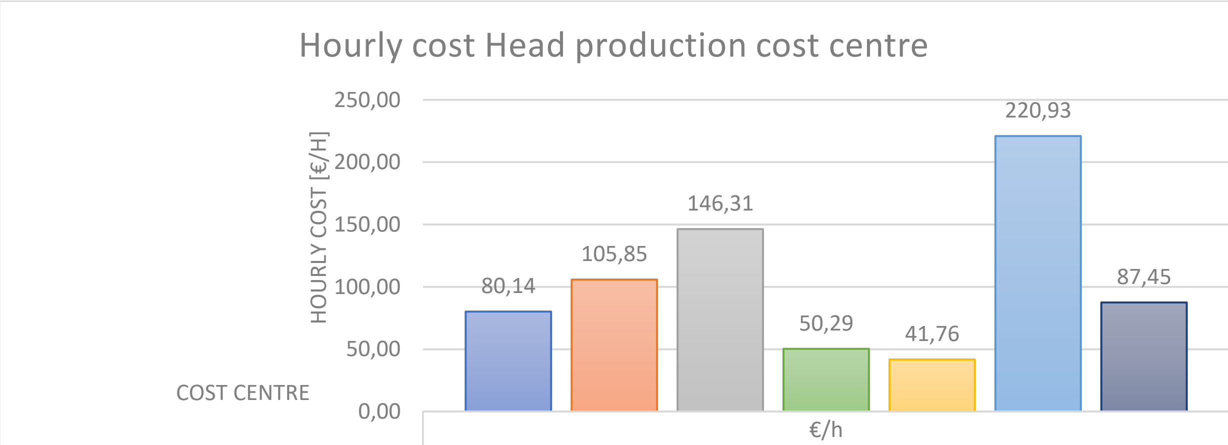
TABLE 21. MACHINING COST CENTER FOR A SINGLE HEAD

Considering the value founded in the research, the production foreseen for a year is of 92 462, that is a satisfying value considering the 80 000 heads per year target production.

Head element machining	**125,01**	**s**
Valve guide and seat installation and machining	1,13	s
Total	126,14	s
N° head machined/year	92472	

TABLE 22. MACHINING TIMES CONSIDERING THE WORKING STATION IN PARALLEL

At last, a histogram that represents the hourly cost for each division of the cylinder head with fixed element production is here provided as a resume of the work performed on the cost analysis of this component.



COST CENTRE	€/h
Wax Bunch production	80,14
Ceramic shell production and dewaxing	105,85
Melting and shell removal	146,31
Cutting and grinding	50,29
Heat Treatments	41,76
Machining	220,93
Valve seat and guide installation and machining	87,45

FIGURE 50. COST CENTRE HOURLY COST PRODUCTION

5.3 Turbocharger assembly

The turbocharger designed for the range extender architecture under development is, as it has been already presented before, characterized by an axial configuration. From previous studies, three compressors divided in, respectively, 7,7 and 8 stages are necessary. A single turbine gas machine is requested to feed the compressors and its scheme is made up of 7 stages.

As a consequence, 44 between rotors and stators must be produced for the three compressors and 14 between rotors and stators are requested to be manufactured for the turbine machine. For these components, the investment casting technological process have been foreseen and, obviously, a machining is requested for the finishing.

FIGURE 51. ROTOR (LEFT) AND STATOR (RIGHT) OF A TURBOMACHINE

During this work, the other important component analysed, for the turbocharger assembly, is the shaft that holds the above-described machine and the electric generator. Due to the quite high length of this feature, it has been thought to divide it in three different segments; that solution allows to overcome the important strain provided by the fatigue phenomenon induced by the moving parts – the machines have been designed in order to work at a maximum speed of 200 000 RPM. The division of the turbomachine on the different segments is the following: first and second compressors are arranged on the first segment, the second portion is dedicated to the electric generator holding and the last part sustains the third compressors and the turbine. That division have been studied and designed in previous work, however, it is dictated by the bearings location and by the different solicitation coming from the machines and by the generator – that is, with its high weight, the most demanding item. Another peculiarity of the turboshaft is the spline machined on it, such a profile has been designed in order to center and coupled the turbomachines' rotors with it.

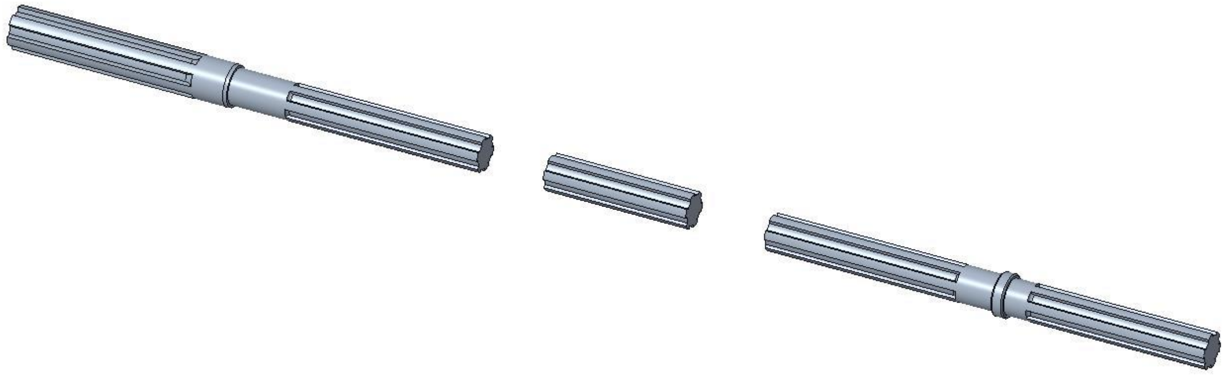


FIGURE 52. TURBOSHAFT'S SEGMENTS DESIGN

Turbocharger assembly cost analysis was, then, proceeded with the analysis of the turbine diffuser, that is basically composed by two items. The first one has been thought to be produced exploiting the already known investment casting process; the second part, instead, due to its nature, will be produced starting from a metal sheet. A folding procedure and a machining working end the manufacturing procedure. The turbine diffuser has been designed in order to extract the maximum possible energy from the exhaust gases. The diffuser, indeed, allows the turbine to gain power from the gases reducing the pressure of the residuals also less than the ambient one, the diffuser will guarantee a final residuals expansion avoiding dangerous and inefficient backflow.

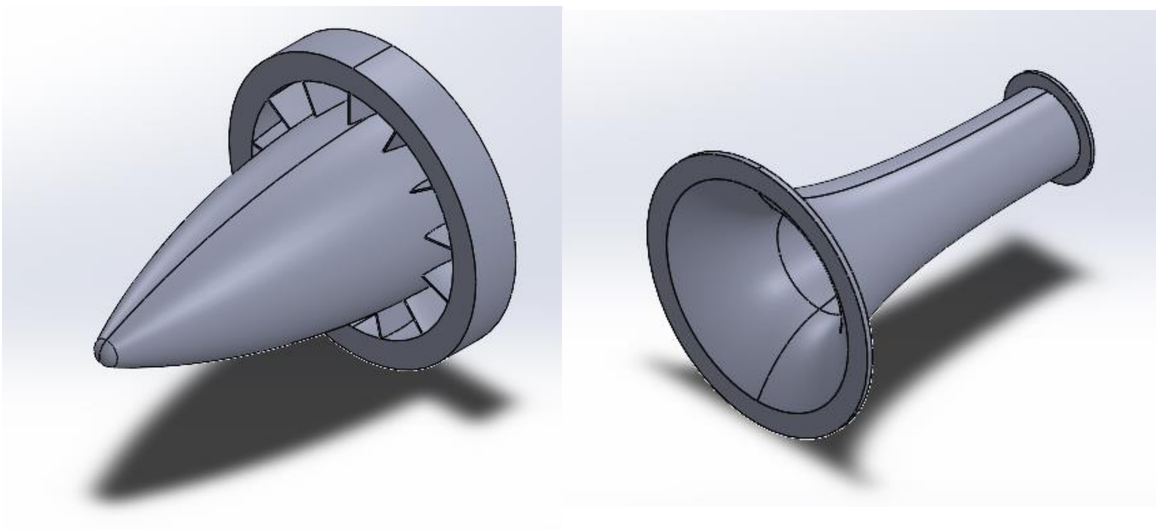


FIGURE 53. TURBINE DIFFUSER, ON THE LEFT THE ITEM CASTED

Moreover, the 4 support flanges production process have been analysed together with the production of the spiral diffuser needed to direct the flow in and out from the turbomachine. Also these items will be casted and, then, machined.

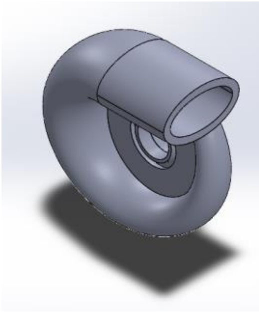


FIGURE 54. SPIRAL DIFFUSER

Last, the turbomachines' cases manufacturing has been studied, in particular, the machining procedure starting from semi-worked tubes have been designed. Moreover, also in that case, a spline connection have been created on the internal surfaces of the housing, this needed born from the necessity of centering and blocking the stators stages of the turbomachines.

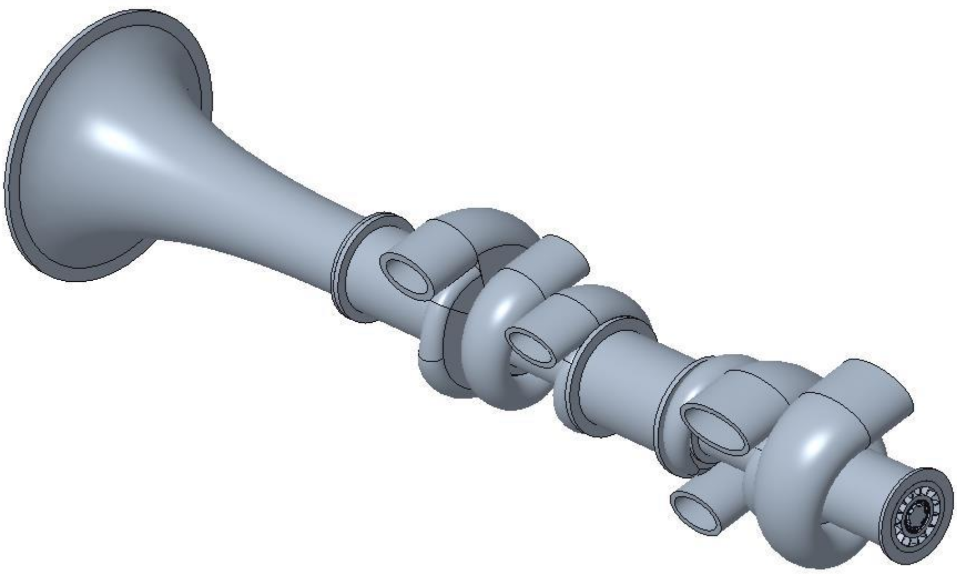


FIGURE 55. THE FINAL TURBOCHARGER ASSEMBLY

This introduction must be ended with a final important consideration, during the work the focus has been dedicated to the components' production, however, in a future work, since this assembly is complicated and it is composed by a high number of items, a specific analysis of the mounting procedure and related costs must be performed and considered.

5.3.1 Weight and Cost Material

As for the cylinder head, the work has started from the components' weights evaluation and, since this topic is strictly related to the materials chosen and its costs, the expenses foresee for the raw have been studied and here presented. Moreover, in that case, a high number of different type of materials have been chosen and exploited due to the different needed of each part and subpart.

The material selected for the rotors' and stators' compressors is an aluminium alloy, in particular, the ASTM 2014 T62 has been chosen. As a convention for the aluminium alloy, the materials of the series 2xxx are composed by Copper added to the aluminium element; the percentage of Cu is represented in a range of 3.9%-5.0%. For what deals with the T62 acronym, it can be said that it states for the heat treatment of the material; indeed, T62 stands for a solubilization followed by a quenching and an age hardening. What it differs from the T6 heat treatment is the timing of the treatment, in this case, indeed, the treatment can be done at every time and, more important, it is performed by the user. The main advantages of the usage of aluminium compounds are the high ductility and workability coupled with a satisfactory corrosion resistance. Moreover, its lightness is an important feature, since at volume parity, it weighs 1/3 with respect to metal alloy. For this specific case, it can be said that this alloy guarantees high strength and machinability also after heat treatments. [35]

For what concerns with the rotors and stators of the turbine, the speech is far more complex, the working background of the quoted items is far more severe with respect to the compressors' one. The first main important aspect is the working temperatures, the first stages of the turbine have to overcome very high heating condition, in particular, temperatures near to 1200 ° can be reached. These conditions, combined with fatigue solicitation coming from the 200 000 rounds per minute of the shaft, set a very demanding working condition. In particular, the fatigue strain must be analysed considering also the creep phenomenon, a type of microscopic event that, when the target component works in ambient at temperature higher than 2/3 of its melting temperature, weakens the material and low down its mechanical properties. [39]

For those reasons, four different materials have been chosen for the turbine stages in order to contain as much as possible the costs; the first two stages, the most stressed, have been designed to be manufactured exploiting a material widely used in the aeronautic field. To be more precise, it is CSMX-4®, a single crystalline superalloy based on Nickel, it is characterized by improved creep-rupture, fatigue and oxidation resistance. It is composed by Nickel and other elements like Chromium, Aluminium, Cobalt and Vanadium. The negative aspect of this kind of material is its difficult to be produced and its consequent high costs. [36]

The third and fourth stages have been thought to be produced exploiting the Waspaloy®, another superalloy made by Nickel and Cobalt to which Aluminium and Titanium are added. Its peculiarity is the capacity of guaranteeing performance up to 650° for rotating parts, avoiding creep and oxidation phenomenon. [37]

For the last four stages, two different materials have been adopted for the stators and rotors, a Titanium alloy, SF-61, has been chosen for the rotors. On the opposite, the stators, since they have to work in less demanding condition provided by their blocked position – no fatigue stress have been applied –, have been thought to use a stainless steel UNS S30815 that ensures a sufficient resistance for the still hot environment. The same iron alloy has been selected for the turbine diffuser, for both its two items. [38]

The support flanges will be manufactured in the same rotors' compressors material, i.e. the aluminium alloy, while for the spiral diffusers, the materials foreseen are the aluminium alloy for the compressors' spirals and the CSMX-4® for the turbine diffuser.

The cases have been thought to be produced starting from a semi-worked tube in the same stainless steel used for the turbine diffuser.

At last, for the turboshaft, a tempered steel 20MnCr5 has been chosen, it is a steel quenched and then relieved exploiting an annealing treatment. It is widely adopted for this kind of application thanks to its high surface hardness and its contact wear resistance.

MATERIAL	DENSITY [KG/M³]
ASTM 2014-T62	2750
CSMX-4®	8972
WASPALOY®	8193
TI-SF61	4560
UNS S30815	7800
TEMPERED STEEL 20MNCR5	7800

TABLE 23. TURBOCHARGER'S COMPONENTS MATERIALS

Exploiting the above reported density values and considering the volume evaluated from the CAD components, it has been possible to evaluate the net weights of the items.

Below it is reported a table that contains the weight evaluated for each component; an important consideration must be performed about the rotors and stators, due to the high number of very similar pieces, average values have been exploited also for the working procedure design. Indeed, an analysis for every single component would be unnecessary and highly time consuming.

ELEMENT	MATERIAL	WEIGHT [G]	D_{MAX} [MM]	VOLUME [MM3]	DENSITY [KG/M3]	QUANTITY
MEAN VOLUME COMPRESSORS' STAGES	ASTM 2014-T62	4,08	25,76	1483,22	2750	44
MEAN VOLUME TURBINE'S STAGES	CSMX-4®	34,41	35,28	3835,69	8972	4
MEAN VOLUME TURBINE'S STAGES	Waspaloy®	29,82	35,46	3639,97	8193	4
MEAN VOLUME TURBINE'S STAGES	UNS S30815	34,49	40,00	4421,59	7800	3
MEAN VOLUME TURBINE'S STAGES	Ti-SF61	9,97	32,07	2185,96	4560	3
DIFFUSER	UNS S30815			213337,14	7800	1
TURBOSHAFT SEGMENT C1 E C2	Tempered steel 20MnCr5	52,76		6764,4	7800	1
TURBOSHAFT SEGMENT EM	Tempered steel 20MnCr5	17,11		2193,62	7800	1

TURBOSHAFT SEGMENT C3 AND T	Tempered steel 20MnCr5	73,56	9430,45	7800	1
SPIRAL DIFFUSER C1-OUT	ASTM 2014 T62	384,29	139741,32	2750	1
SPIRAL DIFFUSER C2-IN+ SUPPORT FLANGE	ASTM 2014 T62	478,43	173975,04	2750	1
SPIRAL DIFFUSER C2-OUT	ASTM 2014 T62	296,72	107898,29	2750	1
SPIRAL DIFFUSER C3-IN	ASTM 2014 T62	226,93	82519,83	2750	1
SPIRAL DIFFUSER C3-OUT + SUPPORT FLANGE	ASTM 2014 T62	363,34	132121,86	2750	1
SPIRAL DIFFUSER T3-IN	CSMX4	1130,2	125974,37	8972	1
SUPPORT FLANGE 1	ASTM 2014 T62	323,74	117723,81	2750	1
SUPPORT FLANGE 2	ASTM 2014 T62	323,75	117726,73	2750	1

TABLE 24. TURBOCHARGER'S ELEMENTS WEIGHTS

Reached this point, firstly, the actual material needed for each piece must be evaluated, then, the final cost for each component can be computed taking into account the unitary market cost of the considered raw material.

Rotors' and stators' quantity of materials have been evaluated exploiting the formula already presented in the cylinder head assembly. Since the same investment casting procedure have been adopted, also the equation coefficients are remained steady. Equation (9) have been used, below it is reported from the previous chapter:

(9) $$TWP = CW \cdot \frac{1}{1-SR} \cdot \frac{1}{Y} \cdot \frac{1}{1-ML} \cdot \frac{1}{1-FSR}$$

COEFFICIENT	DESCRIPTION	VALUE	
CW	Casting Weight	0,0041	kg
SR	Scrap Rate for investment casting	5,00	%
Y	Yield	75	%
ML	Melt loss	6	%
FSR	Finishing and cleaning scrap rate	2	%

TABLE 25. COMPRESSORS' ROTOR AND STATOR MATERIAL USED FOR INVESTMENT CASTING

Applying the formula with the prescribed value, the material needed for the production of a compressors' stator or rotor is 0.01 kg of ASTM 2014-T62.

Equation (9) has also been used for the turbine's stator and rotor:

COEFFICIENT	DESCRIPTION	VALUE	
CW	Casting Weight	0,034	kg

SR	Scrap Rate for investment casting	5,00	%
Y	Yield	75	%
ML	Melt loss	6	%
FSR	Finishing and cleaning scrap rate	2	%

TABLE 26. TURBINE'S STATOR AND ROTOR CSMX-4® NEEDED FOR INVESTMENT CASTING

The amount of material needed for a rotor or a stator of the first two turbine's stages amounts to 0.05 kg.

COEFFICIENT	DESCRIPTION	VALUE	
CW	Casting Weight	0,03	kg
SR	Scrap Rate for investment casting	5,00	%
Y	Yield	75	%
ML	Melt loss	6	%
FSR	Finishing and cleaning scrap rate	2	%

TABLE 27. TURBINE'S STATOR AND ROTOR WASPALOY NEEDED FOR INVESTMENT CASTING

The amount of material needed for a rotor or a stator of the third and fourth turbine's stages amounts to 0.05 kg.

COEFFICIENT	DESCRIPTION	VALUE	
CW	Casting Weight	0,01	kg
SR	Scrap Rate for investment casting	5,00	%
Y	Yield	75	%
ML	Melt loss	6	%
FSR	Finishing and cleaning scrap rate	2	%

TABLE 28. TURBINE'S ROTOR TI-SF61 NEEDED FOR INVESTMENT CASTING

The amount of material needed for the last three turbine's stages rotors amounts to 0.02 kg.

COEFFICIENT	DESCRIPTION	VALUE	
CW	Casting Weight	0,03	kg
SR	Scrap Rate for investment casting	5,00	%
Y	Yield	75	%
ML	Melt loss	6	%
FSR	Finishing and cleaning scrap rate	2	%

TABLE 29. TURBINE'S STATOR, UNS S30815 NEEDED FOR INVESTMENT CASTING

The amount of material needed for the last three turbine's stages stators amounts to 0.05 kg.

Since the same technological process have been used for the spiral diffuser, support flanges and the internal item of the turbine diffuser, the materials needed for each component have been evaluated following the same path. The results obtained are reported in a summary table here:

COMPONENT	MATERIAL	MATERIAL NEEDED FOR INVESTEMENT CASTING	
COMPRESSORS' SPIRAL DIFFUSER	ASTM 2014	0,36	kg
TURBINE'S SPIRAL DIFFUSER	CSMX-4®	1,72	kg
TURBINE'S DIFFUSER INT.	UNS S30815	0,07	kg
SUPPORT FLANGES	ASTM2014	0,36	kg

TABLE 30. DIFFUSERS AND SUPPORT FLANGES MATERIAL NEEDED FOR INVESTMENT CASTING

Different speech must be dedicated to the remaining items, turboshaft is produced starting from a semi-worked circular bar, for that reason the length of each shaft has been the starting point, together with the target production per year – that in this case has been augmented of 1000 unity in order to take into account for defective piece's production –, for the evaluation of the material needed per year. Moreover, a 5% have been considered as scrap and, also, a positive contribution has been taken into account since a certain amount of scrap can be purchased. The semi-worked bar is characterized by a length of 6000 mm and a diameter of 16mm.

Semi-worked length [mm]	6000
Shaft/bar	101
Bars/year	199
Single bar volume [mm^3]	1526814,03
Single bar weight [kg]	11,91
kg/year	2369,92
kg/shaft	0,12

TABLE 31. 20MNCR5 NEEDED FOR A SINGLE SHAFT, RESULT AND COMPUTATIONS

The same procedure has been adopted for the cases and for the external item of the turbine diffuser. In that case, however, the starting semi-worked are respectively tube of three different diameters for the cases and a plate for the diffuser. Below the computations done for the evaluation of right number of semi-worked per year have been reported.

Metal sheet surface	6000000
External Diffuser surface	24616
Diffusers/sheet	240
Sheet/year	88
Sheet weight [kg]	46,8
Material for a single diffuser [kg]	0,21

TABLE 32. UNS S30815 NEEDED FOR A SINGLE DIFFUSER ITEM, RESULT AND COMPUTATIONS

For the cases, a speech a little bit more complex must be dedicated, these components, indeed, have three different diameter and length dimensions. For that reason, three sizes are necessary for the tubes purchasing and, consequently, they have been treated as separate entities for the tubes' quantity/year computation. Then, the average weight for the single generic case have been possible to be implemented.

Tubo	6mt x 15mm thickness
Case/tube 50	84
Case/tube 40	92
Case/tube 56	74
Overall tube/year	1046
Tube weight ϕ50 [kg]	44,66
Tube weight ϕ40 [kg]	33,63
Tube weight ϕ56 [kg]	51,28
Single case material weight [kg]	0,57

TABLE 33.UNS S30815 NEEDED FOR A SINGLE CASE, COMPUTATIONS AND RESULTS

Having in hand all the weight of material needed for the production of all the components that make up the turbocharger assembly, the last piece needed for completing the puzzle is the unitary cost per kg of the material used. The values found come from the market in July 2021, in particular the cost of Waspaloy has been gentle provided by NeoNickel®, CSMX-4® has been given by Cannegon Muskegon®:

MATERIAL	COST/KG	
ASTM 2014	2,11	€/kg
CSMX4	200	€/kg
WASPALOY	180	€/kg
TI-SF61	50	€/kg
UNS S30815	6	€/kg
20MNCR5 BAR Φ18	1,25	€/kg
UNS S30815 TUBE	6,87	€/kg
UNS S30815 PLATE	6,85	€/kg

TABLE 34. COST PER KG, UPDATED TO JULY 2021

The last step for the evaluation of material costs for the turbocharger assembly involves the simple multiplication of the above reported value per kg with the previously computed weight. Below the final results have been provided.

MATERIAL	COMPONENT	MATERIAL COST/COMPONENT	
ASTM 2014	Compressors' rotors and stator	0,01	€
CSMX-4®	Turbine's rotors and stator	10,49	€
WASPALOY ®	Turbine's rotors and stator	8,18	€
TI-SF61	Turbine's rotors and stator	0,76	€
UNS S30815	Turbine's rotors and stator and diffuser	0,32	€
20MNCR5	Turboshaft	0,36	€
ASTM 2014	Compressors' spiral diffusers	0,76	€
CSMX-4®	Turbine’s spiral diffuser	344,40	€
UNS S30815 BAR	Cases	15,68	€
UNS S30815 PLATE	Turbine diffuser	1,34	€

TABLE 35. MATERIAL COSTS FOR TURBOCHARGER ASSEMBLY PRODUCTION

Moreover, where an investment casting is foreseen, also the cost of wax and ceramic shell must be accounted for. The cost of the wax is considered equals to 1.2 €/kg and the ceramic shell costs is assumed equals to 50 €/bunch. Last, for the turboshaft an income is evaluated considering the purchasing of the scrap.

COMPONENT	CERAMIC SHELL COST/COMPONENT	WAX COST/COMPONENT	
COMPRESSORS' ROTORS AND STATOR	0,3333	0,0020	€
TURBINE'S ROTORS AND STATOR CSMX-4®	0,3125	0,0052	€
TURBINE'S ROTORS AND STATOR WASPALOY®	0,3125	0,0049	€
TURBINE'S ROTORS AND STATOR TI-SF61	0,3125	0,0030	€
TURBINE'S ROTORS AND STATOR AND DIFFUSER UNS S30815	0,3125	0,0060	€
SPIRAL DIFFUSER	1,0159	0,1246	€

TABLE 36. INVESTEMENT CASTING MATERIALS COST

5.3.2 Manufacturing Processes and Related Costs

Before presenting the manufacturing cost, it is important to introduce how the production of the different components is organised. Indeed, in order to maximise the saturation of machine and to reduce the costs, some items will be made on the same machines and line. For the practical analysis, it means that the hourly cost centres have been shared between components, lowering their production costs. The starting point of the industrial plant design has always been the same: the 20 000 engines to be manufactured in a year and an additional 1000 unity for defective items substitution.

Following this principle, the final solution is to have three parallel lines for investment casting: one it is dedicated to the compressors' stators and rotors. Second line is devoted to the production of the turbine's stators and rotors; however, since in this case different materials have been treated, four under vacuum melting furnaces have been considered in order to avoid inclusion in the final component. The last line is prone to the manufacturing of the spiral diffusers and of the support flanges, also the internal turbine's diffuser item would be made in this line. The furnaces for the metal melting of this last line are shared with the compressors' and turbine's stages made with the same material.

Since the investment casting procedure has already been presented in chapter 5.2, it will not be repeated here in a detailed version the specific steps of that production method, however below it is reported a scheme that summarize the line division and composition.

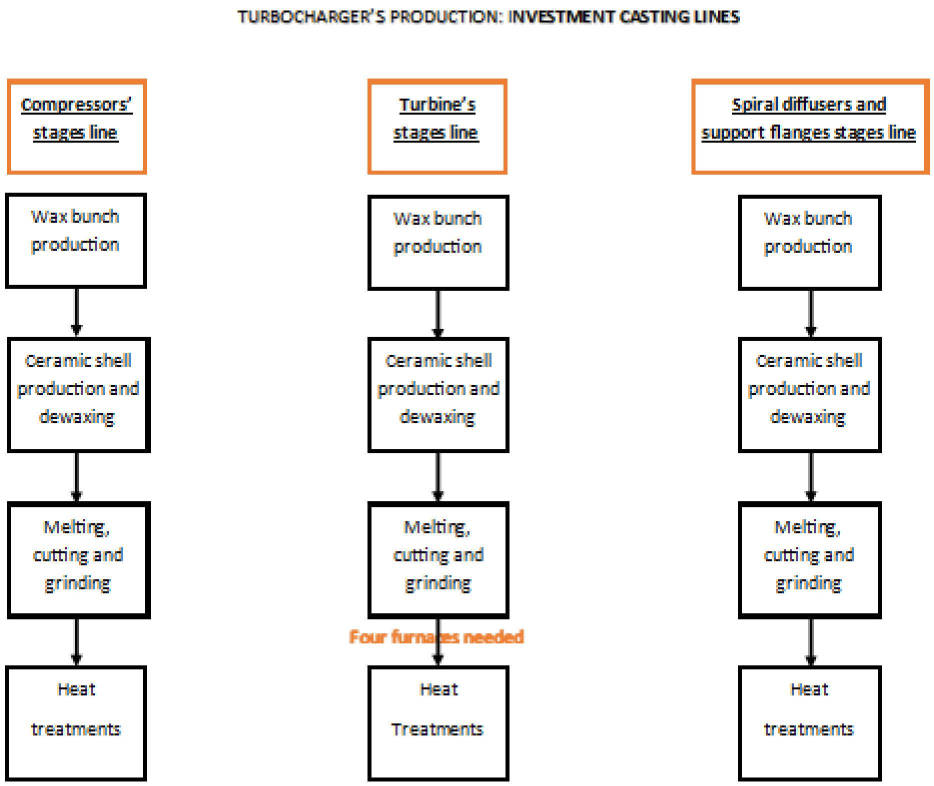


FIGURE 56. TURBOCHARGER'S INVESTEMENT CASTING LINES

Dealing with the machining procedure, the same lines diversification has been used, however, for this transformation, two additional lines have been added since the components that are directly produced starting from semi-worked items must be considered. Summarizing, one work centre is dedicated to the compressors' stages machining, one to the turbine's compressors and rotors production, third line is dedicated to the working procedure of the spiral diffusers and support flange, in the fourth path the external item of turbine's diffuser and cases are processed, while the last workstation provides the final turboshaft component. For the last two lines, some pre-machining working stations must be considered, indeed, a preliminary cutting of the semi-worked material must be taken into account. Moreover, for the turbine's diffuser production, a folding of the plate and a successive welding must be exploited.

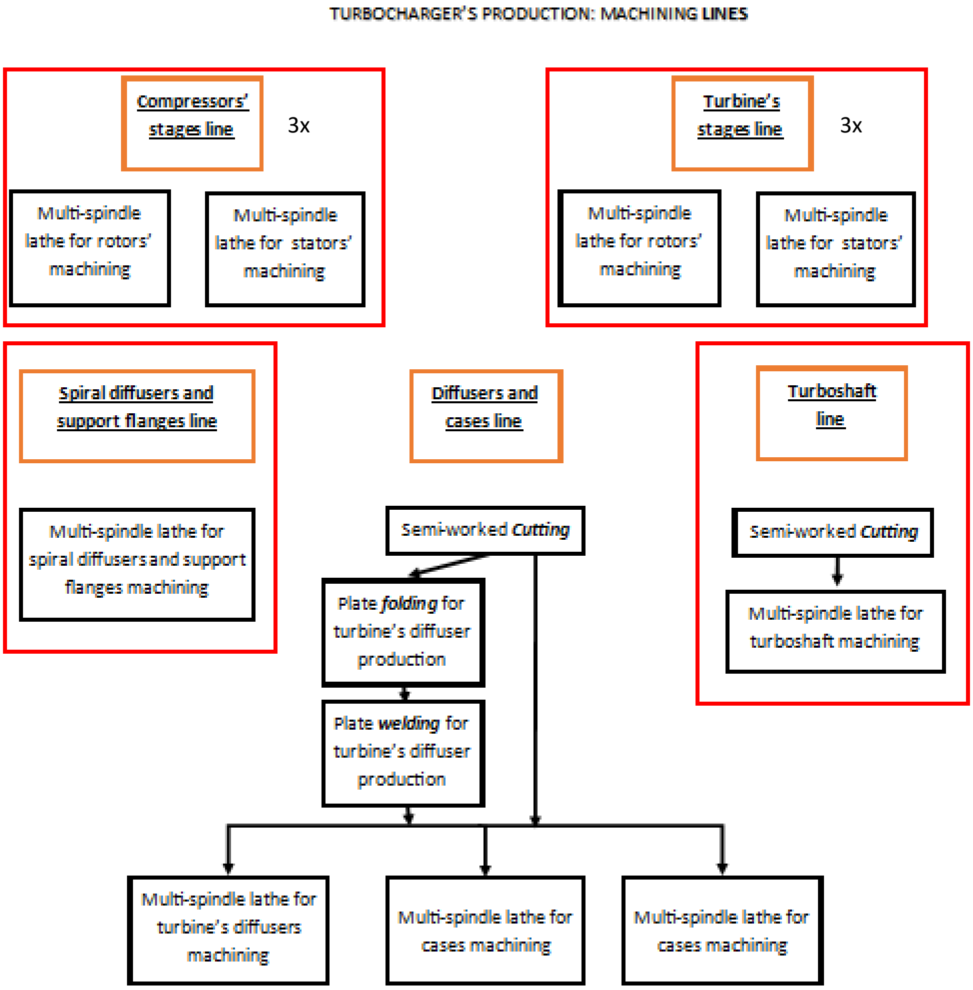


FIGURE 57. TURBOCHARGER'S MACHINING LINES

After the introduction to the turbocharger's component production organization, the next step involves the description of each line, including the machineries selected and their relative costs. Moreover, for the machining process, the transformations foresee and the working cycle for each component will be provided. This process, as for the cylinder head assembly, is necessary for the evaluation of machines needed and for the final cost centres computation. In order to make the discussion clear, each component will be treated once per time and, as for the previous assembly, firstly the investment casting, wherever is foreseen, is discussed before the machining procedure.

Moreover, since for the investment casting, the same equipment as the one chosen for the cylinder head procedure has been selected, it will not be presented again. In particular, wax injector MPI 35 Series and glue injector have been widely exploited for the bunch production. Kawasaki’s robot, PKI’s slurry mixer together with OMI dryer have been chosen for the ceramic shell department. For what, instead, deals with the furnaces, some changes with respect to the cylinder head production have been done due to the smaller dimensions of the components treated. However, they have been selected from LM’s catalogue.

5.3.1.1 Compressors’ rotors and stators production

Compressors’ rotors and stators have been designed and produced through a preliminary investment casting process and a successive machining procedure for the finishing.

As it has already said, the machines, unless where some changes have been performed with respect to the tools selected for the cylinder head, will not be presented again. However, bunch design and times for the investment casting will be analysed.

In this case, due to the compact dimensions of the items, the bunch has been composed by a far higher number of patterns with respect to the cylinder head bunch, moreover, the wax model is composed by a single piece and not by the union of five different patterns. The bunch is characterized by six rows of wax models each composed by 20 items, for a total of 120 wax models per bunch.

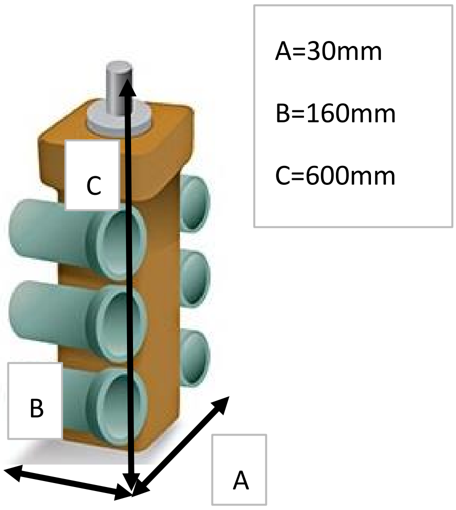


FIGURE 58. COMPRESSORS' STAGES WAX BUNCH DIMENSIONS

Instead, considering the dimensions of each item, the wax flow guaranteed by the wax injector machine – 0.28 kg/s – and the number of figures per mould – 40 –, the time needed for the production of the bunch can be evaluated:

BUNCH PRODUCTION

WAX INJECTION	0,21	s/40 models
SETUP TIME	60,00	s/40 models
SINGLE MODEL PROD. TIME	1,72	s/model
BUNCH PRODUCTION	180,00	s/bunch
OVERALL TIMES	396,76	s/bunch
	6,61	min/bunch
	3,22	s/model

FIGURE 59. COMPRESSORS' STATOR AND ROTOR BUNCH PRODUCTION TIMES

Known the times needed and the target production per year, the hourly expenses for this cost center can be evaluated in **80.14 €/h**.

The subsequent investment casting phase involves the ceramic mould production and successive dewaxing. In this case, since the dimensions of the bunch handled are really contained, smaller furnaces have been selected with respect to the cylinder head. Data and costs have always been provided by LM furnaces and conveyors, in particular, for that application, furnaces LM.1 have been selected for the ceramic shell baking and dewaxing.

FIGURE 60. LM.1 FURNACE

Considering bunch dimensions and furnace space available, 150 bunches are processed together and the resulting time of this production step can be computed.

CERAMIC SHELL PRODUCTION AND DEWAXING

REFRACTORY SHELL APPLICATION	120,00	s/bunch
DRYING	48,00	s/bunch
DEWAXING	8,00	s/bunch
SHELL BAKING	8,00	s/bunch
SETUP AND HANDLING	200,00	s/bunch
OVERALL TIMES	384,00	s/bunch
	6,40	min/bunch
	3,20	s/model

TABLE 37. COMPRESSORS' STATOR AND ROTORS CERAMIC SHELL PRODUCTION AND DEWAXING

The investment and the operating cost of the smaller furnaces are here reported:

- LM.1's 450° furnace costs 40 000 € equals to 10 000 € of depreciation per year, its consumption is 24 kWh and its maintenance is 2000 € per year.
- LM's 1200° furnace costs 40 000 € equals to 10 000 € of depreciation per year, its consumption is 36 kWh and its maintenance is 2000 € per year.

Considering these cost variations, the hourly cost of this department is evaluated in **90.61 €/h.**

The third technological phase involves the metal melting and the cutting and grinding of the models from the bunch. As for the previous step, if the other tools remain unchanged with respect to the cylinder head production scheme, the same could not be said about the under vacuum furnace. In this case, the same model – STVF-Q-160 – has been chosen but with a capacity limited to 50 kg, the new related costs are here reported:

- STVF-Q-160 furnace costs 200 000 € equals to 50 000 € of depreciation per year, its consumption is 96 kWh and its maintenance is 10 000 € per year.

The times needed for this phase, instead, are reported below:

METAL MELTING, CUTTING AND GRINDING		
ASTM 2014 POURING	1,88	s/bunch
VIBRATIONAL SHAKEOUT	60,00	s/bunch
SAND BLASTING	120,00	s/bunch
CUTTING AND GRINDING	200,00	s/bunch
OVERALL TIMES	381,88	s/bunch
	6,36	min/bunch
	3,18	s/model

TABLE 38. COMPRESSORS' STATORS AND ROTORS METAL MELTING, CUTTING AND GRINDING

The hourly cost for the third step is evaluated in **149.76 €/h**.

The last investment casting step deals with the heat treatments of the material. In this case, a first solubilization treatment 8h at 530° must be considered, followed by a quenching and a final aging of 12 hours at 200°. Two furnaces are necessary, 21000 components have been thought to be treated together, dealing with this number an LM.1-1200° furnace can be a sufficient choice. Below the times and the hourly expense for this cost center are reported:

HEAT TREATMENT T62		
SOLUBILIZATION	1,37	s/model
QUENCHING AND SETUP	0,01	s/model
AGING	1,80	s/model
OVERALL TIMES	3,18	s/model

TABLE 39. COMPRESSORS' STATORS AND ROTOR HEAT TREATMENTS TIMES

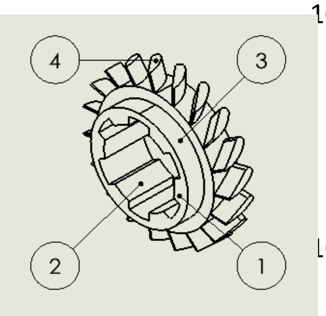
The related cost per hour evaluated is **25.70 €/h**.

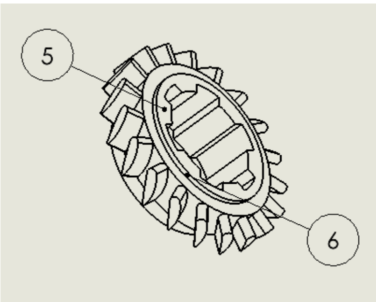
The choices of the furnaces, of the bunch dimensions and of the mould for the wax injection have been purely guided by the same two factors of the cylinder head investment casting procedure design: the target production per year and the needed of equilibrating the times between each department.

The second part of the compressors' stators and rotors technological production procedure involves the machining transformation. Basically, one multi-spindle lathe has been dedicated to the rotor working operations and one to the stator machining. After that the working cycle had been designed and studied, it became necessary to foresee three parallel workstations to satisfy the target production per year, resulting in a department cost tripled.

Rotors' working cycle involves the milling of the planar surface and of the tip of the component. Moreover, a turning procedure is necessary for the finishing of the surface coupled with the stator. Stator's machining, instead, involves a turning for the coupling with the rotor, a milling for the planar surface and a broaching for the external surface that must be coupled with the case. The spline profiles have been chosen following the DIN 5480 with a related module of 0.8. From that rule, it has been possible to evaluate the number of teeth needed and dimensions of the profile. Broach costs and models have been provided by Brighetti Meccanica.

The working cycles designed for the evaluation of times needed for each rotor and stators are reported below, from these results it has been possible to evaluate that three equal workstations must be exploited in parallel.

N° fase	Schizzo	Descrizione	a [mm/min]	Vt [m/min]	N [RPM]	D [mm]	N°	f_t [mm/rev]	N° p	p [mm]	t [s]
10		10.1 Pos.1 centering	-	-	-	-	-	-	-	-	20
		10.2 Milling 1									
		10.2.1 Roughing	3501,41	1100	21883,8	16	2	0,08	1	1,2	0,34
		10.4 Tool change	-	-	-	-	-	-	-	-	1,80
		10.4 Milling 2									
		10.4.1 Roughing	5602,25	1100	35014,1	10	2	0,08	1	1,2	0,07
		10.5.0 Tool change	-	-	-	-	-	-	-	-	1,80
		10.5 Turning 3									
		10.5.1 Roughing	3395,31	400	8488,26	15	-	0,4	1	0,8	0,05
		10.6.0 Tool change	-	-	-	-	-	-	-	-	1,80



	10.6 Turning 4									
	10.6.1 Roughing	1958,83	400	4897,08	26	-	0,4	1	0,8	0,09
	10.7.0 Tool change	-	-	-	-	-	-	-	-	1,80
	10.7 Milling 1									
	10.7.1 Finishing	2476,848802	830	16512,3	16	2	0,075	1	0,8	0,48
	10.8.0 Tool change	-	-	-	-	-	-	-	-	1,80
	10.8 Milling 2									
	10.8.1 Finishing	3962,958083	830	26419,7	10	2	0,075	1	0,8	0,11
	10.9.0 Tool change	-	-	-	-	-	-	-	-	1,80
	10.9 Turning 3									
	10.9.1 Finishing	1782,09	530	11880,6	14,2	-	0,15	1	0,4	0,10
	10.10.0 Tool change	-	-	-	-	-	-	-	-	1,80
	10.10 Turning 3									
	10.10.1 Fininshing	1004,19	530	6694,61	25,2	-	0,15	1	0,4	0,18
	20.1 Pos.2 Centering	-	-	-	-	-	-	-	-	20
	20.2 Milling 5									
	.0.2.1 Roughing	3501,41	1100	21883,8	16	2	0,08	1	1,2	0,34
	20.3.0 Tool change	-	-	-	-	-	-	-	-	1,80
	20.3 Turning 6									
	20.3.1 Roughing	3395,31	400	8488,26	15	-	0,4	1	0,8	0,05
	20.4.0 Tool Change	-	-	-	-	-	-	-	-	1,80
	20.4 Milling 5									
20	20.4.1 Finishing	2476,848802	830	16512,3	16	2	0,075	1	0,8	0,48

20.5.0 Tool change	-	-	-	-	-	-	-	-	1,80
20.5 Turning 6									
20.5.1 Finishing	1664,84	530	11099	15,2	-	0,15	1	0,4	0,11

TABLE 40. COMPRESSORS' ROTORS WORKING CYCLE.

For the sake of brevity, the compressors' stators working procedure will not be reported, only the sketch with the machined surface will be pasted.

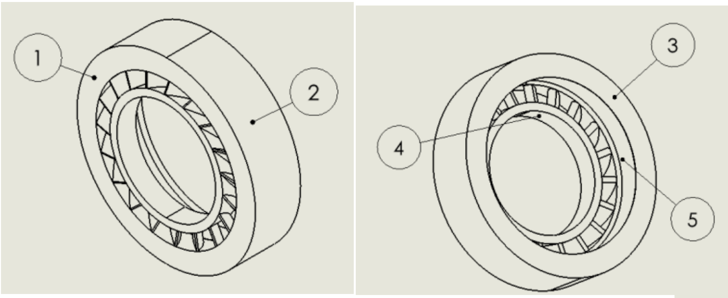


FIGURE 61. COMPRESSORS' STATORS MACHINED SURFACES

The expenses foresee for the machining cost center are here reported:

- CNC Multi-spindle lathe DMG Mori NT4200DCG costs 120 000 € resulting in a depreciation per year equals to 30 000 € per year. Its consumption corresponds to 13.2 kWh and related maintenance is equal to 8400 € per year.

FIGURE 62. DMG MORI NT4200 DCG

- Two qualified operators handle the CNC machine with a wage of 23 000 € per year
- Tool carriers' costs are equal to 3000 €
- Tools costs have been evaluated considered the prescribed Seco Tool duration of 30 mins. Starting from the cutting time evaluated in the working cycle, from the overall productive

working hour and from the overall cycle duration, it has been possible to evaluate the overall tools consumption and costs quantified in 3650 € per year for the rotors' lathe and 92320 € per year for the stators' lathe.

Since each workstation is formed by two lathes, the machine investment must be doubled. Moreover, once the cost of a single workstation had been evaluated, the overall amount of euros have been tripled due to the three workstation in parallel.

The final cost for the machining department has been evaluated in **233.76 €/h**.

Summarizing the cost founded during the compressors' stators and rotors production procedure design, the expenses for each cost center can be pointed out.

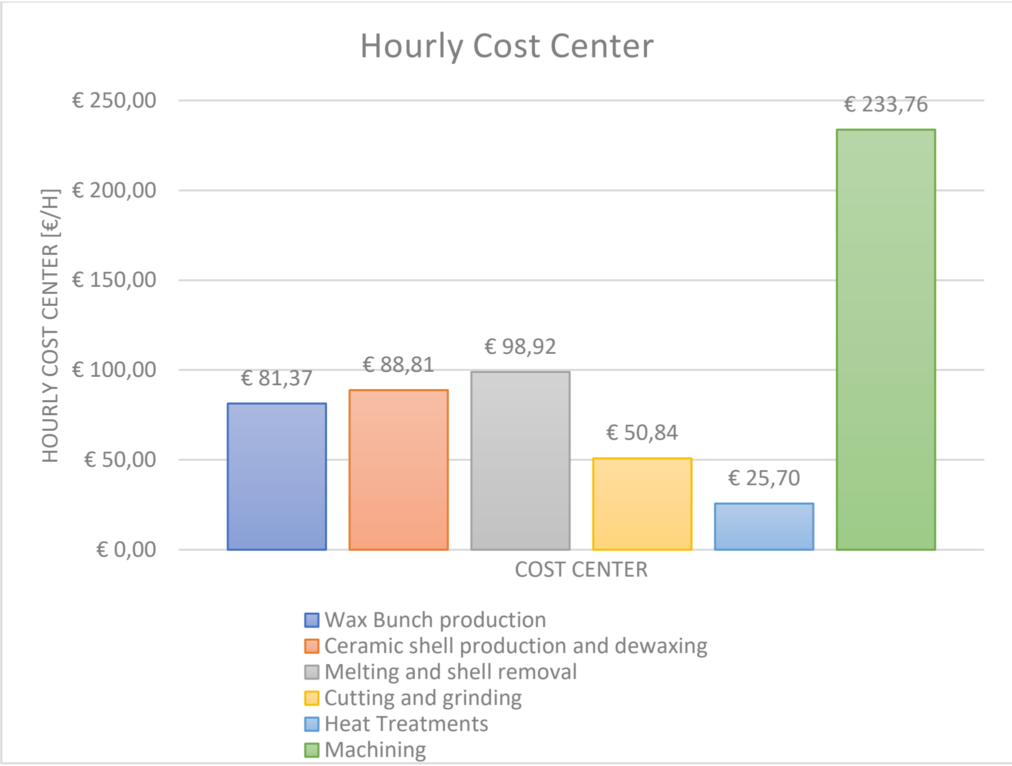


FIGURE 63. HOURLY COST CENTERS FOR COMPRESSORS' STATORS AND ROTORS PRODUCTION

Considering that 240 components will be produced per hour, the cost charged to a single component can be evaluated dividing the hourly cost center for the pieces produced per hour:

Cost Center	
Wax Bunch prod.	€ 0,33
Ceramic shell prod.	€ 0,38
Melting & shell rem.	€ 0,35
Cutting and grinding	€ 0,21
Heat treatments	€ 0,11
Machining	€ 0,97

TABLE 41.COMPRESSORS' STATORS AND ROTORS DEPARTMENT COSTS

5.3.2.2 Turbine's rotors and stators production

Since the turbine's rotors and stators production is very similar to the compressors' one, in this paragraph will be reported the bunch designed, the differences with the previous described production process and, finally, the results gained.

The discrepancies of this process, with the compressors' stators and rotors one, are due to the different number of components that must be produced and due to the necessity of handling four materials. The far lower number of stators and rotors to be produced – 7 rotors and 7 stators for each engine – has led the choice of smaller furnaces for refractory baking, for dewaxing and for the under vacuum metal melting. Moreover, bunches have been composed by a smaller number of items and the figures in the mould for the wax injector machine are only 8.

The bunch has been designed in a way that makes feasible the usage of a smaller furnace – with less cost – at a same time ensuring the target production objective per year and the equilibration between the phases of the investment casting process. So, before presenting the bunch dimension, the furnaces chosen for the treatments across the process, will be presented:

- LM.06 has been selected for dewaxing, ceramic shell baking and heat treatments, its investment corresponds to 25 000 €, equals to a depreciation of 6250 € per year. Its consumption is 15.6 kWh, and its maintenance is 1250 € per year.
- SVTF-Q-160 has been chosen as under vacuum metal melting, in this case, however, the 25 kg capacity has been used. Its investment is 100 000 €, equals to a depreciation of 25 000 € per year. Its consumption is quantified in 48 kWh, with a maintenance of 5000 per year.

Considering this equipment, the bunch has been composed of 4 rows each composed by 12 items, resulting in 48 wax models per bunch.

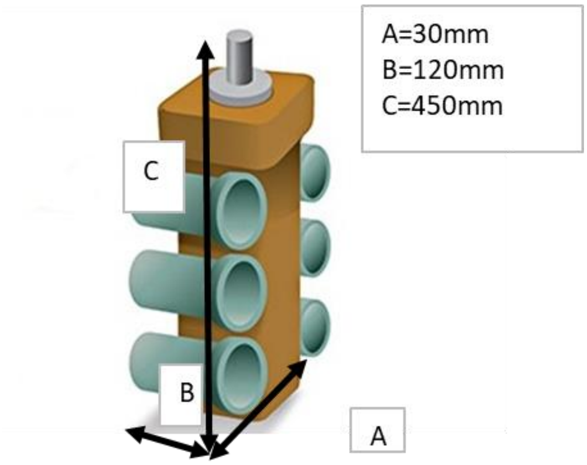


FIGURE 64. TURBINE'S STATORS AND ROTORS BUNCH

Another important difference concerns with the exploitation of four different under vacuum furnaces for the metal melting, since four different materials have been designed to produce the turbine's stages.

Having highlighted these differences, the results gained in terms of times are reported here through a histogram:

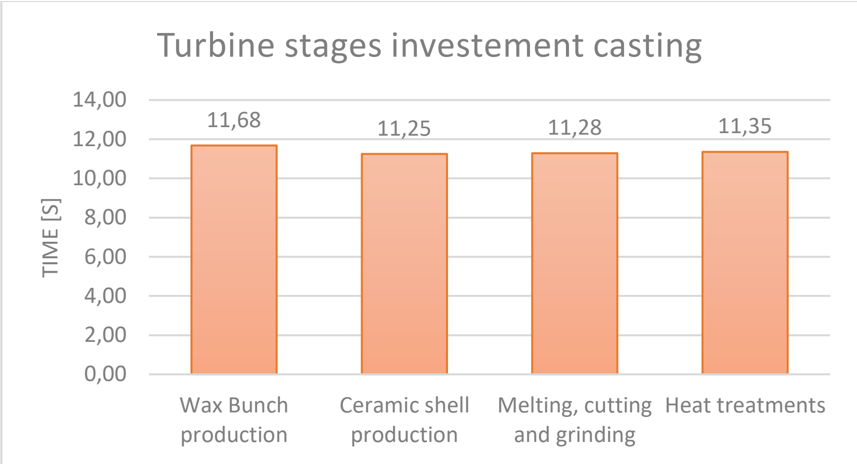


FIGURE 65. TURBINE'S PRODUCTION DEPARTMENT TIMES

Moreover, the hourly expenses for the cost centers involved in the investment casting process are:

- **76.65 €/h** for the wax bunch production
- **83.95 €/h** for the ceramic shell production
- **66.26 €/h** for the cutting and grinding
- **15.83 €/h** for the heat treatments

For what deals with the machining process, it can be said that the operation to be performed on the stators and rotors are exactly the same with respect to the one described for the compressors' stages. However, in that case, higher costs for the tools have been obtained, as it was expected, since the materials treated are far harder than the aluminum alloy used for the compressors' stages. At last, considering the smaller number to be produced in a year, it has been calculated that only two workstations – each one composed by two DMG Mori NT4200 DCG – have been necessary to satisfy the target production. The cost of each workstation is evaluated in 133 €/h that is turned into **266 €/h** considering the two workstations in parallel.

The pieces produced in an hour are 76, the department costs for the production of a single item can be computed; however, in that case the materials involved are 4, therefore, department costs for metal melting are different. Another point is important to be highlighted, indeed, since turbine's spiral diffuser have been produced using CSMX-4 ® while internal turbine diffuser has been designed exploiting UNS S30815, it has been thought to share the metal melting of the respective stages with these two components. This fact turns into a lowering of metal melting costs for both the interested turbine's stages and for the two items quoted.

Cost Center	
Wax Bunch prod.	€ 1,00
Ceramic shell prod.	€ 1,10
Shell Removal	€ 0,40
Cutting and grinding	€ 0,47
Heat treatments	€ 0,72
Machining	€ 3,47

TABLE 42. DEPARTMENT COSTS FOR TURBINE'S STAGES

Cost Center	
CSMX-4 ® Melting	€ 1,00
Waspaloy ® Melting	€ 1,25
TI-SF61 Melting	€ 1,66
UNS S30815 Melting	€ 1,25

TABLE 43. DIFFERENT COST FOR METAL MELTING DEPARTMENT

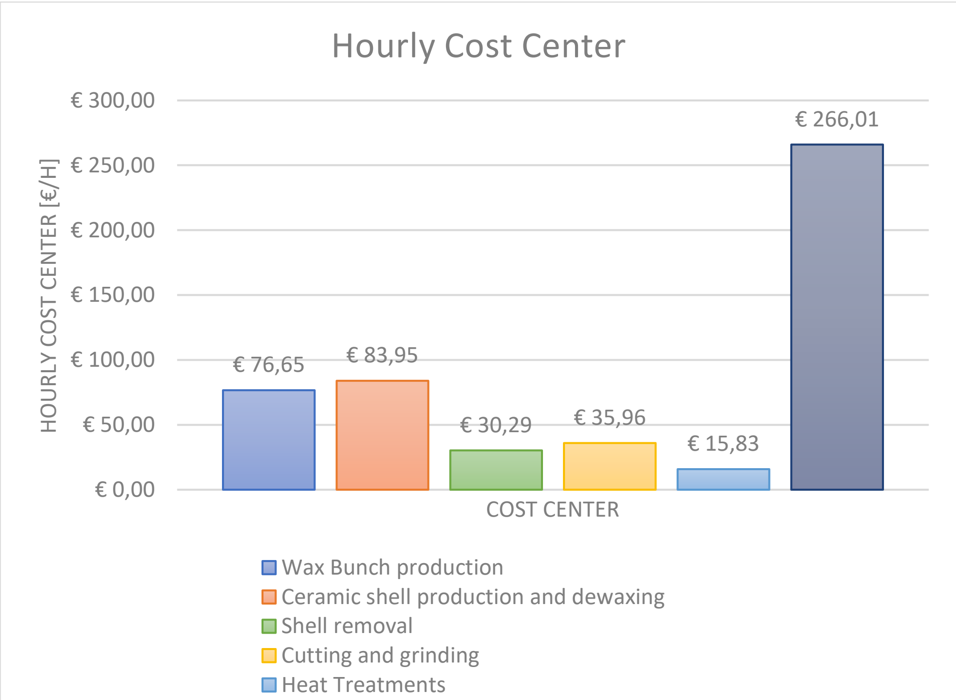


FIGURE 66. TURBINE'S HOURLY COST CENTERS

5.3.3 Spiral diffusers, support flanges and turbine's diffuser internal item production

The spirals, flanges and the turbine's diffuser internal item have been designed to be made exploiting the known investment casting procedure, moreover, a machining process has been designed for finishing the cast products.

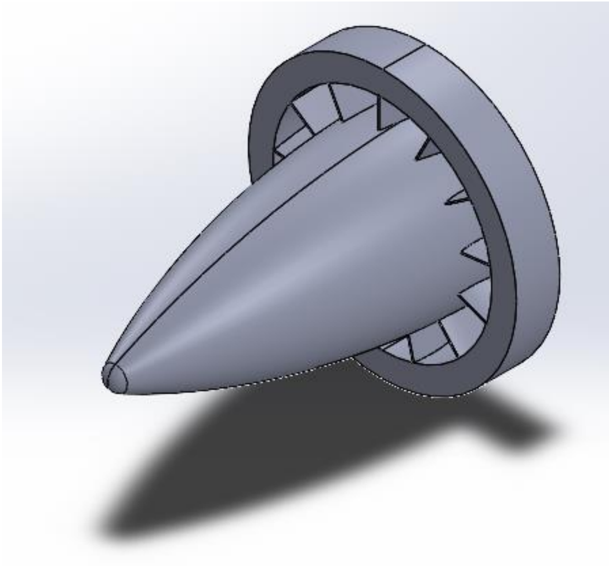


FIGURE 67. TURBINE'S DIFFUSER INTERNAL ITEM

As for the turbine's stages production, since the equipment is pretty the same with respect to the compressors' stages production, the emphasis of this paragraph will be given to the main differences with respect to the compressors' stators and rotors manufacturing, to the bunch configuration and to the results grabbed.

For the production of these components, the only difference with respect to the compressors' stages production deals with the furnaces exploited for the heat treatments, indeed, in this case the components treated have dimensions bigger with the one of rotors and stators. Therefore, the furnaces selected for the heat treatments are roomier and they correspond to the already presented – for the cylinder head production – LM 1.68E furnaces. The cost of this furnace has been copied here:

- LM's 1200° furnace costs 100 000 € equals to 25 000 € of depreciation per year, its consumption is 96 kWh and its maintenance is 4000 € per year.

Dealing with the bunch configuration, a 4 rows scheme is used, as the one exploited for the turbine's stages, in this case, however, 7 items have been foreseen for each row, resulting in 28 wax models per bunch. Below the dimensions of the designed bunch are reported:

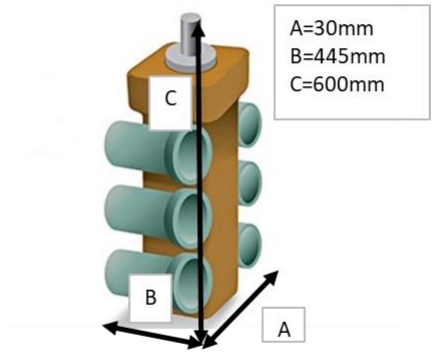


FIGURE 68. BUNCH DIMENSIONS

The under vacuum furnaces exploited for the metal melting, as it has been already said in the previous paragraphs, are shared with the respective material compressors' and turbine's stages.

The times of each investment casting phases are reported in a histogram as for the previous components:

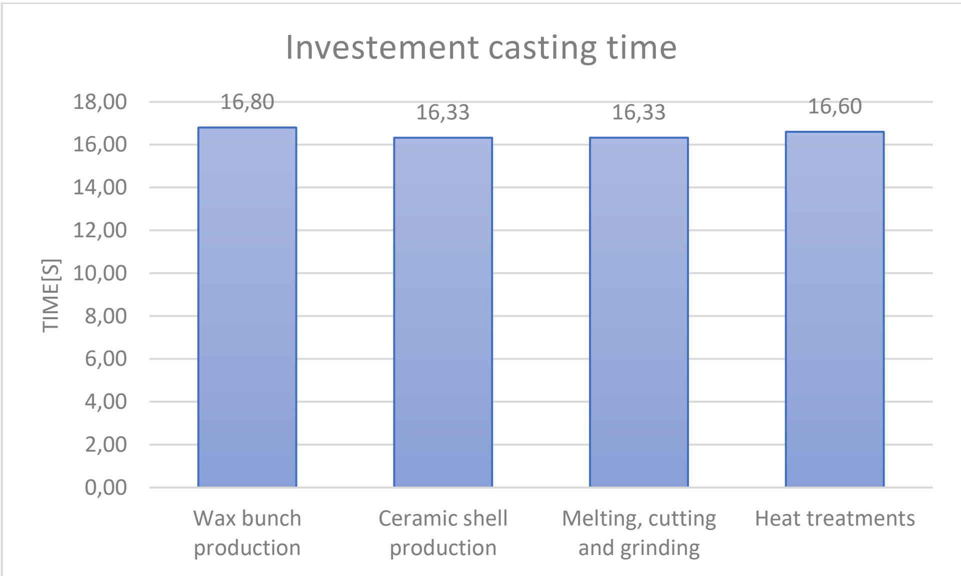


FIGURE 69. SPIRAL DIFFUSERS, SUPPORT FLANGES AND TURBINE'S INTERNAL DIFFUSERS INVESTMENT CASTING TIMES

The resulted hourly cost evaluated are here reported:

- **76.65 €/h** for the wax bunch production
- **86.10 €/h** for the ceramic shell production
- **79.67 €/h** for the cutting and grinding

For what deals with the machining procedure, it involves mainly the finishing of the spiral diffusers surfaces that have to enter in contact with the compressors' and turbine's stator. The working cycle – that will not be reported here – is composed mainly by the milling of the planar surfaces. Moreover, a turning and broaching procedure is foreseen for the coupling with the turboshaft. The cost calculated for the machining department is composed by:

- CNC machine Landonio MEC-T 3000/5 purchased for 120 000 €, equals to a depreciation of 30 000 € per year. Its consumption is 13.2 kWh with a maintenance of 8400 € per year.

FIGURE 70. CNC WORK CENTER

- Tools cost evaluated in 45990 € per year with 1800 € needed for the tool carriers purchasing.
- A qualified CNC worker with a wage of 23000€ per year.

The hourly cost computed for the machining cost center results into **77,04 €/h**.

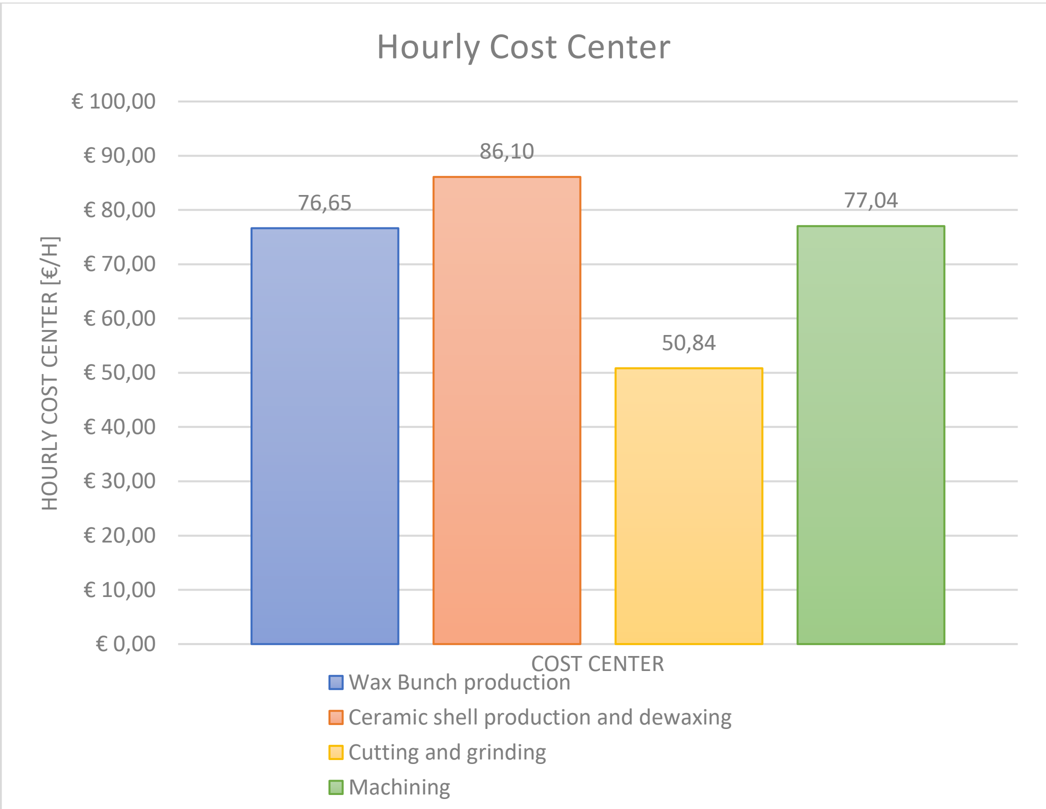


FIGURE 71. HOURLY DEPARTMENTS' COSTS

In this case, the pieces produced in an hour corresponds to 49 unity. The subsequent costs for each department are:

Cost Center	Wax Bunch prod.	€ 1,56
	Ceramic shell prod.	€ 1,75
	Cutting and grinding	€ 1,03
	Machining	€ 1,57

TABLE 44. DEPARTMENT COSTS FOR EACH COMPONENT

Dealing with the melting and heat treatments departments, a different speech must be performed since, as it has already stated, these departments are shared with compressors' and turbine's stages. For this reason, the departments' costs differ between the materials adopted for the production. It means that the turbine's spiral diffuser exploits the metal melted by the same furnaces used for the first two turbine's stages that are made of the same CSMX-4 ®, the same speech is valid for the internal turbine's diffuser and for the last three turbine's stators and for the compressors' spiral diffusers, support flanges and compressors' stages.

For what deals with the heat treatments, since the space available does not allow to share the furnaces with the stators and rotors, dedicated furnaces must be used, increasing the cost of that cost center.

Considering this, the evaluated costs for melting and heat treatment departments are here reported with respect to the material used.

	Material	Melting	Heat treatment
Cost Center	ASTM 2014	€ 0,20	€ 1,05
	CSMX-4 ®	€ 1,00	€ 5,27
	UNS S30815	€ 1,25	€ 5,27

TABLE 45. MELTING AND HEAT TREATMENT DEPARTMENTS' COST WITH RESPECT TO THE MATERIAL USED

5.3.2.4 Turbine's diffuser external item and turbomachines' cases production

In this chapter, the production of the external turbine's diffuser item and of the turbomachines' cases will be analyzed. Due to the shape of these components, since less machining operations must be performed, it has been thought to manufacture them starting from semi-worked material in order to reduce the costs and the production times.

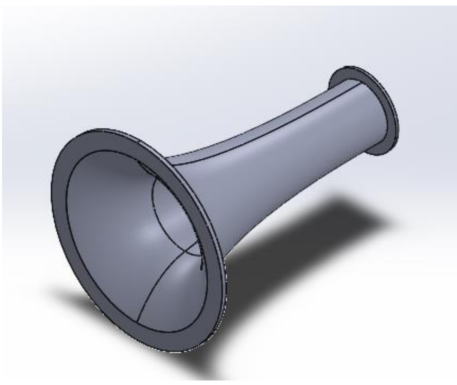


FIGURE 72. EXTERNAL TURBINE'S DIFFUSER ITEM

To produce the turbine's diffuser, it has been foreseen to exploit a metal plate as a starting material. UNS S30815 plate must be cut, then a folding followed by a welding operation must be performed to model the desired final shape. A final machining procedure has been used for finishing the component.

For what concerns with the cases' production, it has been used tube of different dimensions – based on the different cases' dimensions – a cutting procedure followed by a machining procedure must be performed.

Talking about working cycle, it can be said that, for the turbine's diffuser production, after the cutting, folding and welding operation, milling of the planar surface in contact with the final turbine's stage must be foreseen. For what deals with the cases, instead, the discussion is more complex since, beyond the milling of the surfaces in contact with the spiral diffusers, a preliminary turning operation must be performed to adapt the diameter to the final desired measure. Moreover, a broaching procedure must be considered for the shaping of DIN 5480 profile needed for the centering of turbomachines' stators.

COMPONENT	TIMES	
DIFFUSER	223,9	s
COMPRESSOR 1'S CASE	389,7	s
COMPRESSOR 2'S CASE	333,7	s
COMPRESSOR 3'S CASE	393,3	s
CASE TURBINE	393,3	s

TABLE 46. DIFFUSER AND CASES PRODUCTION TIMES

Four workstations have been designed for the presented components' production, for the cutting phase the following equipment has been chosen:

- Bekamak's band saw model BMSO-420-XS costs 50 000 € equals to 12 500 € of depreciation per year, its consumption is 18 kWh and its maintenance is 3500 € per year. At this voice also 5250€ per year has been computed for the band substitution.
- A worker with a wage of 20 000€ has been foreseen.

This compartment is shared for the cases' and turbine's diffuser production, its hourly cost is equal to **20.49 €/h**.

The next two areas have been necessary exclusively for turbine's diffuser production, the first workstation is the folding one, the tools and staff necessary are:

- Gasparini's CN folding press model X-press 30/1250, its cost amounts to 66 000€ for a depreciation per year equals to 16 500€. Its consumption is 9.6 kWh with a maintenance of 4620 € per year
- A worker devoted to the press control with a wage of 20 000€ per year.

The hourly cost of this department results in **19.19 €/h**.

After the folding operation, the diffuser needs to be closed with a welding, for this transformation a specific area has been designed, it is composed by:

- AWF-1500 automatic welding machine has been selected; the investment related to its purchasing is 6000€ for a depreciation per year equals to 1500€. Its consumption is evaluated in 3.6 kWh with a maintenance of 420 €.
- Wire and gas consumption has been calculated, the expense per year is 2000€
- Welding template cost corresponds to 3000 €
- An operator is responsible for this zone with a wage of 20000 € per year.

The hourly cost of this area amounts to **14.73 €/h**.

The last zone is dedicated to the machining procedure, it is shared between cases and turbine's diffuser. For satisfying the target production, three workstations in parallel must be exploited, with a tripled hourly cost.

The area is composed by:

- Multi-spindle lathe DMG Mori NT4200 DCG, the investment corresponds to 120 000€ with a depreciation of 30 000€ per year, its consumption is 13.2 kWh with a maintenance of 8400 € per year.
- Tool's carriers costs are equal to 7200 €.
- Tool's consumption – considering always the guidelines provided by Seco Tools – has been evaluated in 19040 € for the diffuser transformation and 150 760 € for the cases' working operation.
- A specialized operator with 23000€ of wage per year.

Considering the three workstations in parallel, the overall hourly cost is **124.31 €/h**.

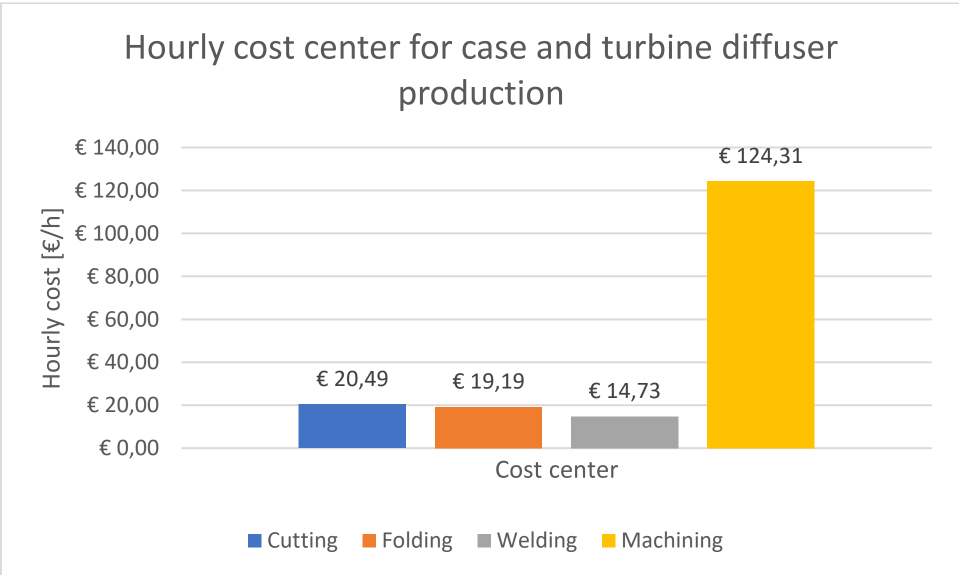


FIGURE 73. DEPARTMENT HOURLY COST CENTER

To satisfy the production per year goal, 27 pieces must be manufactured in an hour, considering this value, it can be evaluated the production cost of a single diffuser and of a case by dividing the hourly cost with the hourly production:

Cost Center	Cutting	€ 0,75
	Machining	€ 4,55

TABLE 47. CUTTING AND MACHINING COST FOR DIFFUSER AND CASE PRODUCTION

For what deals with the diffuser production, folding and welding areas must be added to the cost above reported, in this case the hourly cost is divided for the diffuser produced in an hour that amounts to 5 pieces per hour, the resulting costs are:

Cost Center	Welding	€ 2,53
	Folding	€ 3,51

TABLE 48. FOLDING AND WELDING DIFFUSER PRODUCTION COSTS

5.3.2.5 Turboshaft production

The last component of the turbocharger's assembly analyzed is the turboshaft. This component has been designed to be produced starting from a circular bar that, after a cutting operation, is machined in order to get the final component shape.

The cutting operation involves the preliminary sizing of the turboshaft's segments and, after that the machining operations are concluded, foresees the cutting of the grasping. Moreover, the cutting area includes also a drill press for the blocking of the semi-worked on the CNC machine.

The machining operations include the turning procedure in order to get the desired diameters and the milling of the splined profile necessary to couple the shaft with rotors. Moreover, since the shaft is divided in three segments, the planar surfaces that are in contact must be milled too.

The overall times of the segments' working cycle have been calculated and the results are here reported:

SEGMENT	TIMES	
SEGMENT COMPRESSOR 1 AND COMPRESSOR 2	427,4	s
SEGMENT ELECTRIC MACHINE	353,1	s
SEGMENT COMPRESSOR 3 AND TURBINE	436,2	s

TABLE 49. OVERALL WORKING CYCLE TIMES FOR TURBOSHAFT PRODUCTION

Considering the times obtained from the working cycle analysis and the target yearly production, three machining workstations must be used in parallel. For what deals with the cutting operation, instead, it is sufficient a single cutting area.

The cutting area is made up of the below tools and machines:

- Bekamak's band saw model BMSO-420-XS costs 50 000 € equals to 12 500 € of depreciation per year, its consumption is 18 kWh and its maintenance is 3500 € per year. At this voice also 1080€ per year has been computed for the band substitution.

- Drill press costs 3000 € equals to a depreciation of 750 € per year, its consumption is 1.32 kWh and the drill bit substitutions are computed in 500 € per year.
- A specialized worker is responsible for this area with a wage of 23000 €.

The overall hourly cost of this department is equal to **22.31 €/h**.

The machining area, instead, is composed by three workstations in parallel, each one includes:

- DMG Mori NT4200 DCG multi-spindle lathe that costs 120 000€ for a depreciation of 30 000€ per year, its consumption amounts to 36 kWh with a maintenance of 8400 €.
- Seco Tool's consumption is evaluated in 39050€, 9660€ and 44600€ per year for, respectively, the machining of compressor 1 and 2 segment, electric machine segment and compressor 3 and turbine machining.
- A specialized worker is devoted to the CNC machine control with a wage of 23000€ per year.

This cost, as it has been already stated, must be tripled since the number of workstations in parallel are three.

The hourly cost of this area is different for the three workstations in parallel since the segments' lengths and the machining operations are slightly different.

The hourly cost for the machining of compressors 1 and 2 segment is equal to **39.66 €/h**, the second segment hourly expenses correspond to **32.01 €/h** and the machining operations for the last segment cost **41.11 €/h**.

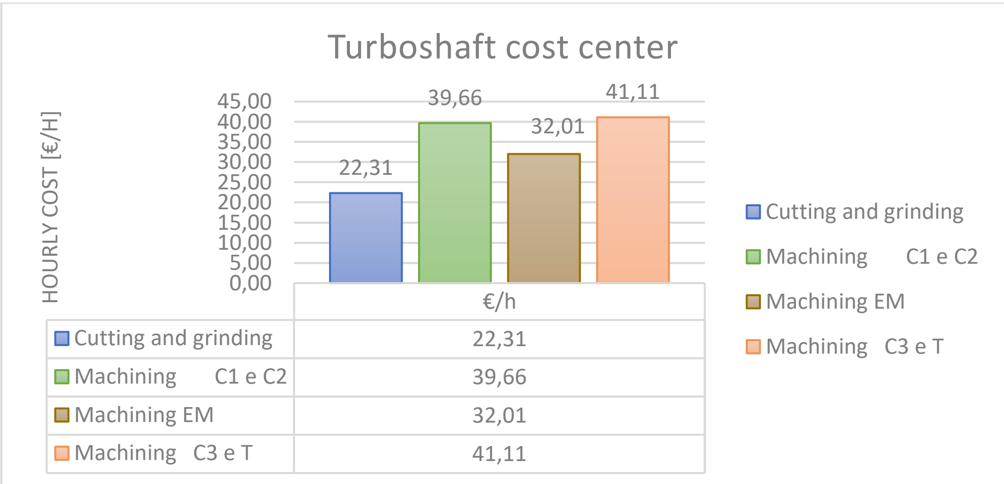


FIGURE 74. TURBOSHAFT'S DEPARTMENTS HOURLY COST

Considering the target objective, 5 shafts must be produced in an hour, the subsequent production costs for a single turboshaft are here reported.

Cost center	Cutting and grinding	€ 4,28
	Machining C1 e C2	€ 7,62
	Machining EM	€ 6,15
	Machining C3 e T	€ 7,89

TABLE 50. TURBOSHAFT'S PRODUCTION COSTS

5.4 Basement assembly

The basement assembly is one of the most important group of the internal combustion engine, it holds the crankshaft, the countershafts with their electric generator and the cylinder liner. In this chapter the production costs for the basement element and for the cylinder block will be evaluated.

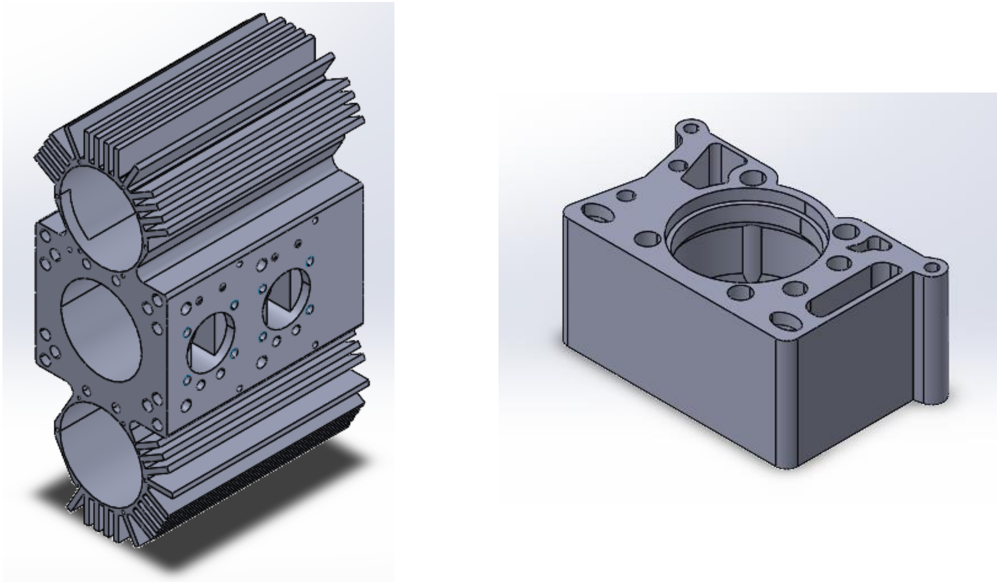


FIGURE 75. BASEMENT ELEMENT (LEFT) AND CYLINDER BLOCK (RIGHT)

For both the basement element and for the cylinder block, the extrusion process is the technological method chosen for the production. This industrial transformation has already been chosen during the previous design work performed by Ing. Zampini, indeed, to allow the exploitation of this procedure, some constraints must be respected like a minimum thickness of components' walls. [40]

The advantages of such an industrial transformation are:

- The quickness of the process and of the tools mounting.
- Tools' costs are far lower with respect to other industrial process like casting.
- High productivity.
- Complex shape can be realized. [41]

Direct extrusion process is based on the production of components through the exploitation of pressure force. The basic principle that led this technological transformation is the pushing of a billet through a designed matrix that allows to realize the near final shape of the item. Such a process can be conducted both in hot or cold conditions, the first procedure is suggested since less friction forces are experienced and less risk of cracking; however, cold extrusion ensures higher mechanical characteristic, good finishing surfaces and higher productivity.

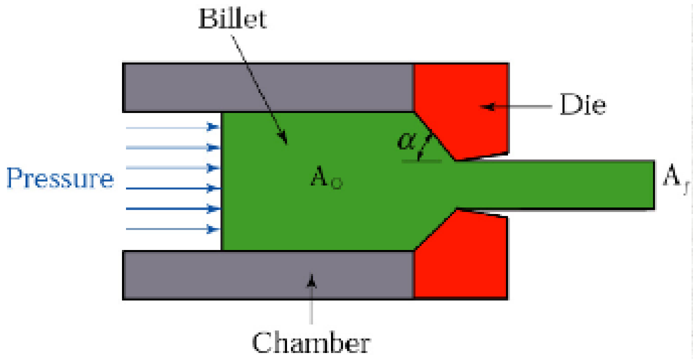


FIGURE 76. EXTRUSION PROCESS

SOURCE: *ATZENI E., "TECNOLOGIA MECCANICA-12 DEFORMAZIONE PLASTICA", TORINO, 2019*

Reverse extrusion method is another type of procedure for the extrusion operations, it involves the pushing of the matrix towards the billet, so, in this case, the billet is still while the die is the movable part; the major benefit of this method is the very low friction forces applied to the billet.

The main parameters that influence the process are

- The extrusion ratio that is the division between initial section area and final section area $R=A_0/A_f$.
- The die opening angle α.
- The friction coefficient.
- The billet temperature.
- The extrusion velocity.

After the extrusion operations, a machining is needed, indeed, the rugosity guaranteed by that process is not satisfactory, moreover, a high precision could not be ensured. [42]

In this case, the direct hot extrusion has been the procedure chosen, the process involves, firstly, the cutting of the billet in the desired length dimension; then, a pre-heating phase must be overcame. The sub-sequent step is the proper extrusion process that must be followed by a pressing for releasing the stress generated during the extrusion. A new cutting is then necessary for eliminating the grasping from the final component. The process is then ended with the heat treatments.

At last, the machining operations are performed to finish the final product.

5.4.1 Weight and Cost Material

As for the other assembly, the starting point of cost analysis has been the material cost evaluation. The standard procedure has involved the net volume evaluated through the exploitation of the CAD model; then, known the volume and the material used, net weight has been computed and, during the last step, the total amount of material needed to produce the components has been pointed out.

The material selected for both the basement element and the cylinder block is an aluminium alloy of the 6xxx series. This alloy series is composed by aluminium, magnesium and silicon. The specific alloy chosen is AA6081-T6, the heat treatment prescribed by the acronym T6 is a solubilization, followed by quenching and successive artificially aging. Its peculiarities are the good resistance values and its easy machinability.

Analysing the CAD models, the net volumes and, consequently, the net weights have been calculated:

ELEMENT	MATERIAL	WEIGHT [G]	VOLUME [MM3]	DENSITY [KG/M3]	QUANTITY
BASEMENT ELEMENT	AA 6081 - T6	8118,90	3006999,02	2700	1
CYLINDER BLOCK	AA 6081 - T6	463,52	171672,33	2700	4

TABLE 51. NET VOLUMES AND WEIGHTS OF BASEMENT ASSEMBLY

For the definition of the semi-worked billet volume, the starting point is the final volume of the basement, indeed, during the extrusion process the volume remains unchanged.

(10) $$V_f = A_f \cdot l_f = A_0 \cdot l_0 = V_0$$

The other fixed point is the diameter of the billet that have been chosen following the empirical rule for which the diameter must be 1.5 times the diameter of the circumference that encloses the final manufact.

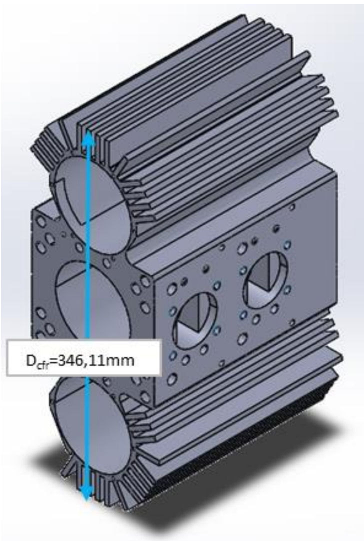


FIGURE 77. DIAMETER OF THE CIRCUMFERENCE THAT ENCLOSES THE BASEMENT

(11) $$D_0 = 1.5 \cdot D_{cfr}$$

The resulted billet has a diameter of 500 mm and a length of 16.18 mm, this second dimension must be increased of 8.09 mm that is the scrap deriving from the grasping and it is computed as the half of the billet length.

The standard billet provided by the company Rodacciai Spa has a length of 6 meter and a cost per kilogram equals to 2.10 €/kg, known all these parameters, the yearly cost of the materials needed to satisfy the target production can be evaluated:

AA6081-T6 cost per kg	2,1	€/kg
V_0 Semi-worked initial volume	4765218	mm^3
Billet Volume	1178097245	mm^3
Billet Weight	3180,86	kg
Cost/Billet	6679,81	€
Bars/year	85	
Material Cost/year	567783,97	€
Material Cost/Single basement	27,04	€

TABLE 52. BASEMENT ELEMENT PRODUCTION MATERIAL COST

The same discussion can be applied to the cylinder block production, since the same technological process has been adopted, the semi-worked initial volume can be evaluated starting from the final volume of the cylinder block thanks to the volume conservation. Then, since the diameter is defined as 1.5 times the diameter of the circumference that encloses the final component, the dimensions of the semi-worked can be pointed out and, at this point, billets needed in a year with the related expenses can be evaluated.

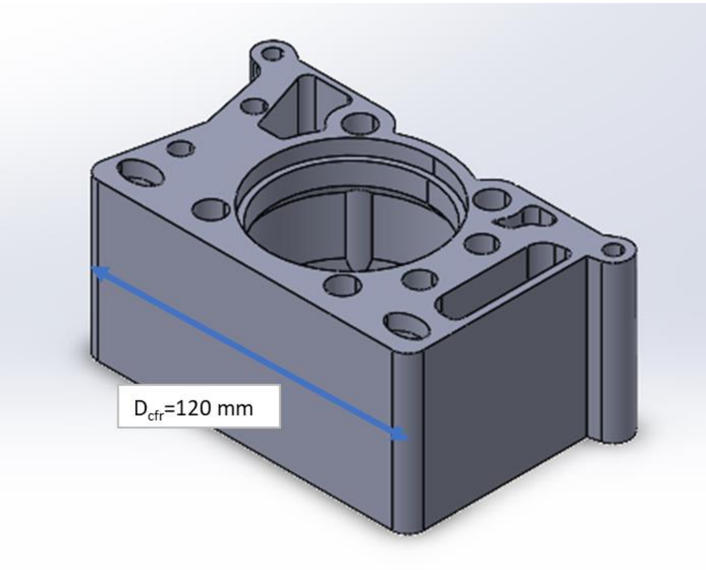


FIGURE 78. DIAMETER OF CIRCUMFERENCE THAT ENCLOSES THE CYLINDER BLOCK

A billet with 190 mm diameter has been chosen from the Rodacciai Spa catalogue, the length of the semi-worked has been calculated in 5,79 mm improved of 2,89 mm due to the scrap deriving from grasping. The results obtained are here reported:

AA6081-T6 cost per kg	2,1	€/kg
V_0 Semi-worked initial volume	246729,1	mm^3
Billet Volume	170583144,8	mm^3
Billet Weight	460,6	kg
Cost/Billett	967,2	€
Bars/year	122	
Material Cost/year	117999,2	€
Material Cost/Single cylinder block	1,40	€

TABLE 53. CYLINDER BLOCK PRODUCTION MATERIAL COSTS

5.4.2 Manufacturing Processes and Related Costs

As it has already been introduced, the technological process exploited for both the basement and cylinder block production is the extrusion. This plastic deformation procedure does not need only a press for the proper transformation, but it must be performed also some preliminary operations, especially in case – like the one designed in this work – of hot extrusion.

Four main areas have been thought and designed for the complete transformation of starting billet to the rough components obtained after the extrusion. Then, a machining procedure has been necessary to finish the items and to perform some features that cannot be carried out during the plastic deformation process.

During this paragraph, the logical production order will be followed, in the first part the equipment and machinery needed for the extrusion process will be analysed with its related cost, then, the machining step will be studied. Moreover, for the sake of clarity, the cylinder block technologic production process will be treated separately from the basement.

5.4.2.1 Basement Element production

The transformation of the billet into the rough basement involves four main step that have been thought to be done in four different cost centres.

The *first area* is the zone devoted to the cutting of the bar – that it is 6 meters long – into shorter pieces, precisely, they have to be chopped in pieces of the right length evaluated in the paragraph 5.4.1. In this way, the semi-worked can be ready to overcome the extrusion procedure.

The equipment and the crew foresee for this area is:

- An automatic band saw, Bekamak's saw model BMSO-420XS has been chosen, its cost accounts for 50 000 € resulting in a depreciation of 12 500 € per year. Its consumption corresponds to 18 kWh and its maintenance in a year costs 3500 €.

FIGURE 79. BEKAMAK BMSO-420XS

- Considering the billet diameter and its material, 30 000 € must be considered for the bandsaw blade substitution in a year.

- A worker is responsible of this area with a wage of 20 000 € per year.

The resulting department hourly cost is computed in **26.93 €/h**.

The *second area* is dedicated to the pre-heating of the semi-worked components since the hot extrusion process has been chosen. This step is very important because the items must be at the right temperature and must be homogeneously heated in order to avoid fracture and rupture due to approximative pre-heating.

The time calculated for a right pre-heating phase is 30 minutes, this value must be divided, as it has happened in the previous components' discussions, for the number of semi-worked heated together. For satisfying the target year production and considering the available hours in a year, 150 semi-worked must be processed, for this purpose an LM's industrial oven has been chosen, in particular the model .02 has been chosen.

Following the furnace presentation, the equipment chosen and related costs are here presented:

- LM .02 furnace costs 30 000 € resulting in a depreciation of 7500 € per year. Its consumption is 5.4 kWh and its maintenance amounts to 1500 €.
- A wage is assigned to the furnace handling with a wage of 20 000 € per year.

The overall hourly expenses for this cost center are evaluated in **15.41 €/h**.

The *third area* is the proper extrusion zone, basically, in this department, an extrusion press must be exploited. Moreover, another important voice for the cost is the substitution of the extrusion matrix; this part is the shaped metal hole through which the semi-worked is forced to pass. Since in this case a complex shape must be obtained, the matrix is normally divided in two parts, the first one separates the semi-worked while the second is devoted to the re-welding procedure: thanks to the huge pression forces and facilitated by the high temperature, the parts that are separated in the previous step are here re-composed in the final component configuration.

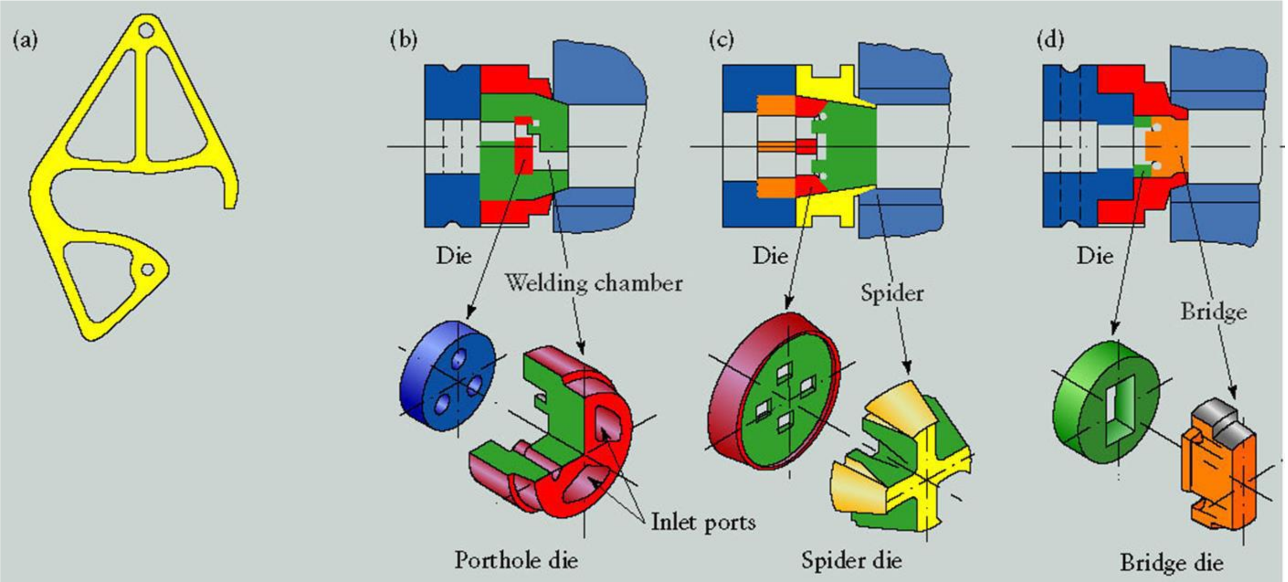


FIGURE 80. MATRIX FOR WELDING CHAMBER METHOD
SOURCE: ATZENI E.," TECNOLOGIA MECCANICA-012 DEFORMAZIONE PLASTICA", TORINO, 2019

In order to choose a proper press, the force needed for the extrusion process must be evaluated. The force necessary to extrude the billet can be computed considering two main aspects: the work needed to deform the material and the work necessary to overcome the friction between the billet and the matrix.

(11) $$W_{def} = \sigma_0 \cdot V_0 \cdot ln\frac{A_0}{A_f}$$

The deformation work can be computed considering the starting dimensions of the billet V_0 and A_0, the deformation resistance of the material at the considered temperature σ_0 and the final section area of the component A_f.

The deformation resistance has been evaluated with the following formula:

(12) $$\sigma_0 = k' \cdot (ln\frac{A_0}{A_f} \cdot 6 \cdot v_f \cdot \tan\alpha \,/D_0)^m$$

K' and m are the rheological constant, they are typical parameters for the considered material at a determined temperature, for the case analyzed their respectively values are 44 and 0.12. V_f is the feed velocity of the press, it can be provided by the press dealer and in that case a typical value of 0.18 m/min are used. α is the sliding angle, for the aluminum 45° is used. D_0, instead, is the billet diameter.

The second contribution, instead, can be evaluated with the following formula:

(13) $$W_f = \frac{\pi}{2} \cdot D_0 \cdot l_0^2 \cdot \sigma_0 \cdot f$$

σ_0 is the already evaluated deformation resistance of the material, f is the friction coefficient between the billet and the matrix, D_0 and l_0 are, respectively, the diameter and the length of the semi-worked.

Knowing these two contributions, the overall force needed can be computed dividing the overall work for the initial semi-worked surface and considering the yield coefficient of the extrusion process that can be evaluated in 0.4.

Exploiting this procedure, the necessary force is equal to 33700 kN. [43]

For the evaluation of the matrix consumption, the tons of material extruded is the parameter exploited for the computation. Alto Aluminum Tooling – a company specialized in the aluminum matrix production – has indicated 25 tons has a realistic value for the maximum material that a single matrix can extrude before the wear becomes unacceptable. The amount of material that must be extruded in a year corresponds to the weight of a semi-worked multiplied for the number of bars needed in a year, that has already been evaluated before, and is equal to 85. The weight can be easily evaluated multiplying the aluminum density – 2750 kg/m^3 – for the volume of the component that, known the diameter and the length of the bar, can be turned into 1.18 m^3. The tons extruded in a year result to be 270.37. At this point, dividing this value for 25 tons – the extrudable threshold of each mould – 11 matrixes must be considered for a year. However, since some problems could occur during production, 14 matrixes will be accounted for with a safety margin.

The costs of the equipment selected for this area are here reported:

- The extrusion press chosen is the Souhtwark 4000MT, a press able to ensure a maximum pressure of 40000 kN, its cost is 250 000 € for a depreciation per year of 62500 €. Its consumption is quantified in 96 kWh and its maintenance corresponds to 17500 €.

FIGURE 81.SOUTHWARK 4000MT EXTRUSION PRESS

- The cost for a single matrix accounts for 10 000 €, considering the value founded above, the overall cost per year is 140 000 €.

FIGURE 82. EXTRUSION MATRIX EXAMPLE

- A qualified worker is dedicated to the press handling with a wage of 23000 € per year.

Considering all these costs the overall hourly expense for this department is **85.78 €/h**.

The *last cost centre* is dedicated to the heat treatment of the rough component, the same furnace chosen for the pre-heating department is selected, however, since in this case a solubilization and a successive artificial aging must be foreseen, two furnaces must be purchased. As before, the choice of the furnaces has been done on the basis of the target year production; 150 components can be baked together. The times needed calculated are here reported:

150 Basement at a time	Time needed		Relative time	
Pre-Heating	8	h	12	s
Solubilization	8	h	192	s
Aging	12	h	288	s
Quenching	60	s	60	s
Overall time			552	s

TABLE 54. EXTRUSION'S FURNACES TIMES

The costs for this department are:

- 30 000€ for each LM .02 furnace that corresponds to 7500 € of depreciation per year. The consumption of each furnace is 5.4 kWh and the maintenance is equal to 1500 €.
- A worker handles this area with a wage of 20 000 €.

The overall hourly expense for this cost center is **65.48 €/h**.

Being ready the basement for the finishing step, the machining working cycle will be presented and its related costs will be pointed out. For the sake of clarity, the entire working cycle will not be reported here, however, the machining operations will be explained, and related costs will be analyzed.

Considering the available space inside the CNC machine, three basements have been thought to be worked together in order to minimize the centering times. The operations considered deal with the milling of all the surfaces that are in contact with other components and so that have to be precise and the more possible planar. These surfaces are the two plates in contact with the 4-cylinder blocks – operation 3 in figure 83 –, the surfaces, respectively, coupled with the distribution's transmission case and with the cover of the counter shaft – operation 1 in figure 83. The other operation is the drilling of all the holes and ducts perpendicular to the extrusion direction, and so that cannot be done during the plastic deformation phase – operations 5,6,7,8 in figure 83. The last process, that must be taken into account for, is the boring of the holes for the connecting rod – operation 4 in figure 83.

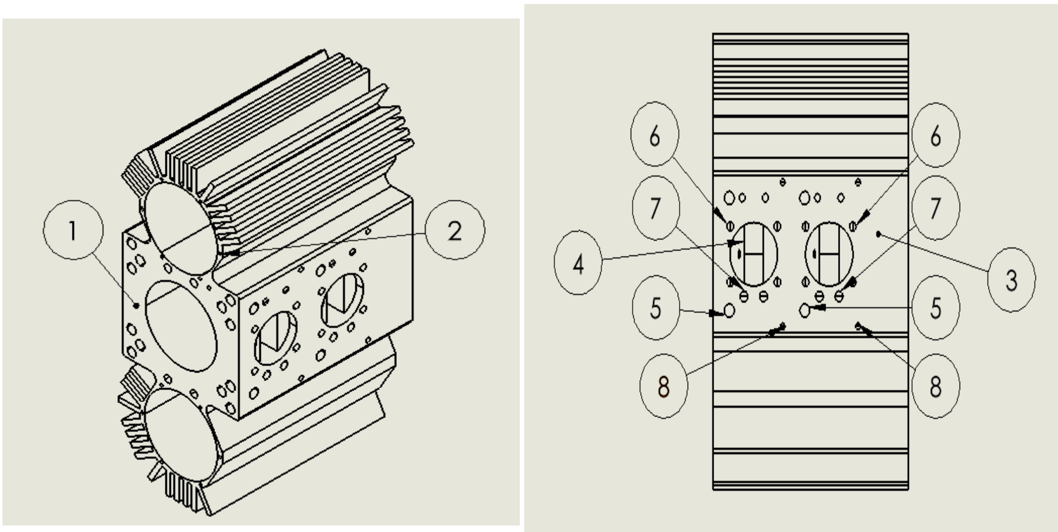


FIGURE 83. MACHINING OPERATIONS FORESEE IN THE WORKING CYCLE

During the working cycle design, beyond the time needed for each machining operation – that has been calculated using the cutting parameter provided by Seco Tools and, obviously, considering the cutting dimension – 120 seconds have been evaluated for the centering of the components inside the CNC machine; the tools change have been taken equals to 1.8 seconds that is the value prescribed for the selected machine.

The time needed for a complete working cycle – so considering the complete working of three basement including the roughing and finishing – is 23.69 min, that turns into 7.89 min for a single basement. This value is satisfying since allows to use only one workstation ensuring low-cost machining center. Below the voice that makes up the equipment and the crew are reported together with the hourly cost:

- CNC machine Okuma MU6300V costs 300 000 € resulting in a depreciation per year equals to 75 000 €. Its consumption corresponds to 13.2 kWh and related maintenance is equal to 21 000 € per year.
- A qualified operator handles the CNC machine with a wage of 23 000 € per year
- Tool carriers' costs are equal to 22800 €
- Tools costs have been evaluated considered the prescribed Seco Tool duration of 30 mins. Starting from the cutting time evaluated in the working cycle, from the overall productive working hour and from the overall cycle duration, it has been possible to evaluate the overall tools consumption and costs quantified in 67000 € per year.

The overall hourly cost is quantified in **65.48 €/h**.

Having in hand all the departments' costs, the cost for the production of a single basement with respect to each cost center can be pointed out:

Cost Center	Cutting	€ 4,19
	Pre heating	€ 2,39
	Extrusion	€ 13,33
	Heat treatments	€ 4,79
	Machining	€ 10,18

TABLE 55. PRODUCTION COST FOR A SINGLE BASEMENT WITH RESPECT TO THE COST CENTER

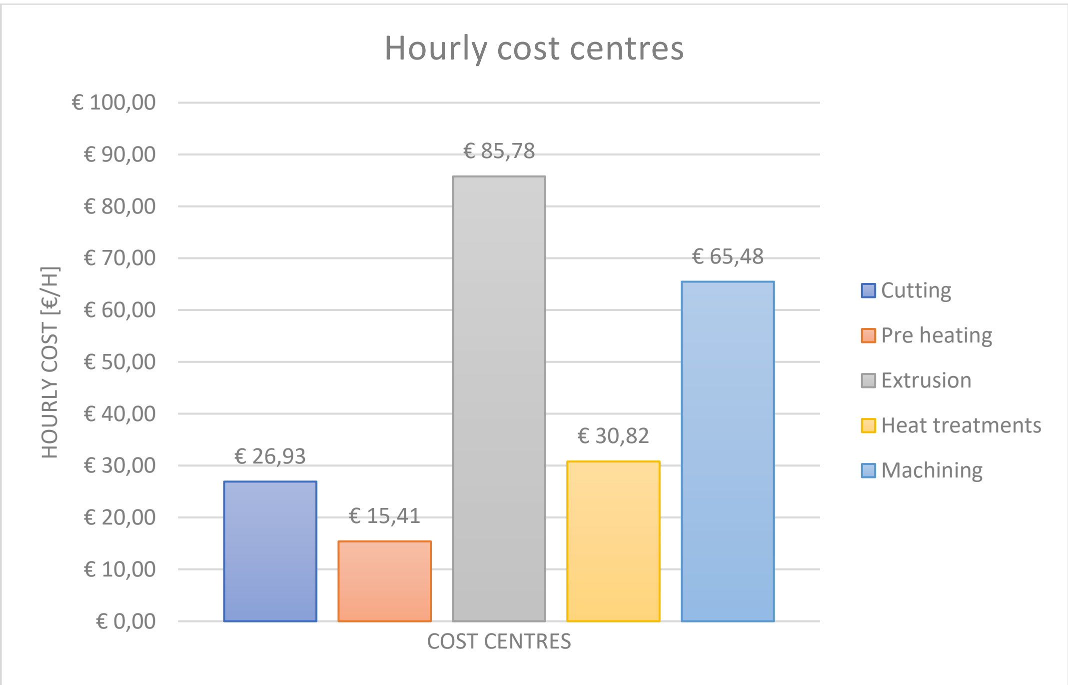


FIGURE 84. DEPARTMENTS' HOURLY COSTS

5.4.2.2 Cylinder Block Production

The cylinder block is the component devoted to holding the cylinder liner – the component that guides the piston during its strokes – and, with its tunnels and holes, it hosts the liquid cooling and lubricant passages. In the analyzed engine, both the lubrication and the cooling are performed by oil, as it is previously described.

Since the material used for the cylinder block is the same of the basement element and the shape of the designed component is predisposed to the extrusion process, the same technological cycle described for the basement has been chosen.

If the industrial production scheme designed remains unchanged with respect to the basement production, the same could not be said for the equipment chosen, indeed, the component shows far smaller dimensions and weight if compared with the basement element. Moreover, in this case, as it could be noted from the Bill of Material provided in chapter 5.1, 4-cylinder blocks must be produced per each engine, resulting in a target production of 84 000 elements considering defective components and spare parts.

As for the previous components' analysis, in the first part of this paragraph the extrusion process will be handled, while, in the second part, the machining procedure will be described. However, before pointing out the costs foreseen for the production, some calculations have been performed and will be reported here.

The first part of the cylinder block production procedure design has involved the calculation of the press force necessary to extrude the component, in order to choose a press well suited for the scope, moreover, the target year production and the furnaces' times have been considered for the ovens choice.

The calculations performed for the extrusion process have been the same described in the previous paragraph, so the equations (11), (12) and (13) have been exploited using the new dimension for the cylinder block element. The result obtained is that the press must provide a minimum force equals to 4350 kN. For what deals with the matrix consumption, 3 matrixes have been evaluated as the consumption of a year, considering the material to be extruded in a year; however, for safety reasons, 6 matrixes will be considered.

Concerning with the times inside the furnace, they have been considered the same as the one used in the basement element analysis, however, in this case, since more components must be produced in a year, the relative times for component must be reduced. This needed has led the choice of furnaces with high internal space available, LM .07 has been the best choice in order to bake 675 cylinders at a time.

675 Cylinders at a time	Time needed		Relative time	
Pre-Heating	8	h	2,67	s
Solubilization	8	h	42,67	s
Aging	12	h	64,00	s
Quenching	60	s	30,00	s
Overall time			139,33	s

TABLE 56. CYLINDER BLOCK FURNACES' TIMES

The cylinder block production cost for the four departments previously described for the basement are reported below.

The *pre-heating* cost center organization and equipment are here reported together with the costs:

- An automatic band saw, Bekamak's saw model BMSY 440 has been chosen, its cost is 20 000 € resulting in a depreciation of 5000 € per year. Its consumption corresponds to 4.8 kWh and its maintenance in a year costs 1400 €.

FIGURE 85. BEKAMAK BMSO-420XS

- Considering the billet diameter and its material, 7610 € must be considered for the bandsaw blade in a year.
- A worker is responsible of this area with a wage of 20 000 € per year.

The resulting department hourly cost is **16.62 €/h**.

The *pre-heating* is equipped with LM furnaces model .07 – the choice has been exploited above – so the equipment chosen and related costs are here presented:

- LM .07 furnace costs 40 000 € for a depreciation of 10000 € per year. Its consumption is 18 kWh and its maintenance amounts to 2000 €.
- A wage is assigned to the furnace handling with a wage of 20 000 € per year.

The overall hourly expenses for this cost center are evaluated in **18.08 €/h**.

Next area is the *extrusion department*, the expenses of the equipment selected for this cost center are:

- The extrusion press chosen is the press 700T, a press able to ensure a maximum pressure of 700 tons, approximately corresponding to 6867 kN, its cost is 128 000 € for a depreciation per year of 3200€. Its consumption is quantified in 96 kWh and its maintenance corresponds to 8960 €.

FIGURE 86. 700T EXTRUSION PRESS

- The cost for a single matrix accounts for 10 000 €, considering the value founded above, the overall cost per year is 60 000 €.

- A qualified worker is dedicated to the press handling with a wage of 23000 € per year.

Considering all these costs the overall hourly expense for this department is **52.95 €/h**.

The last area is the *heat treatment zone*, using the already mentioned LM .07 furnaces and considering two ovens needed for the treatments, the machinery and staff needed is:

- 40 000€ for each LM .07 furnace that corresponds to 10 000 € of depreciation per year. The consumption of each furnace is 18 kWh and the maintenance is equal to 2000 €.
- A worker handles this area with a wage of 20 000 €.

The overall hourly expense for this cost center, considering the needed of two furnaces with doubled handling costs, is **48.19 €/h**.

The last part for the cylinder block production is the analysis of machining process. Working cycle has been designed, from this starting point the cost of this technological transformation has been ruled out in order to complete the production scheme of this component.

As for the previous component, the integral working cycle has not been reported to not overload the discussion, however, the main working step will be described. To evaluate the time of each machining, the cutting parameters indicated by Seco Tools for the utensils chosen has been exploited together with the dimensions of the features to be worked.

In order to minimize the setup time and to avoid the necessity of using two workstations in parallel, 10 cylinders have been thought to be worked together since the working platform of the CNC center is big enough.

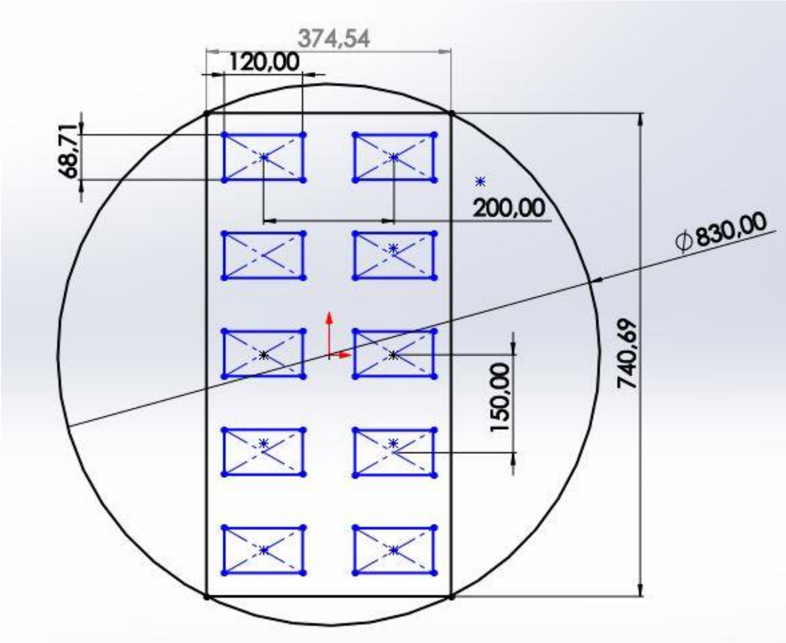


FIGURE 87. CYLINDERS MACHINING POSITIONING

The transformations foreseen for the component are the milling of the plate in contact respectively with the cylinder head and with the basement – 1 and 5 in Figure 88. Then, the milling of the internal edge of the cylinder must be considered for a perfect coupling with the liner – operation 2 in Figure 88. The last transformation considered is the drilling of the various ducts for the cooling and lubricant passage – in Figure 88 operations 3,4 and 6. Moreover, 150 seconds have been accounted for the centring and positioning of the plate; 600 seconds for the cylinder block mounting on the plate have been also evaluated, however, since it is an operation that must be performed manually while the CNC is working on another plate, it is not counted for the overall working cycle.

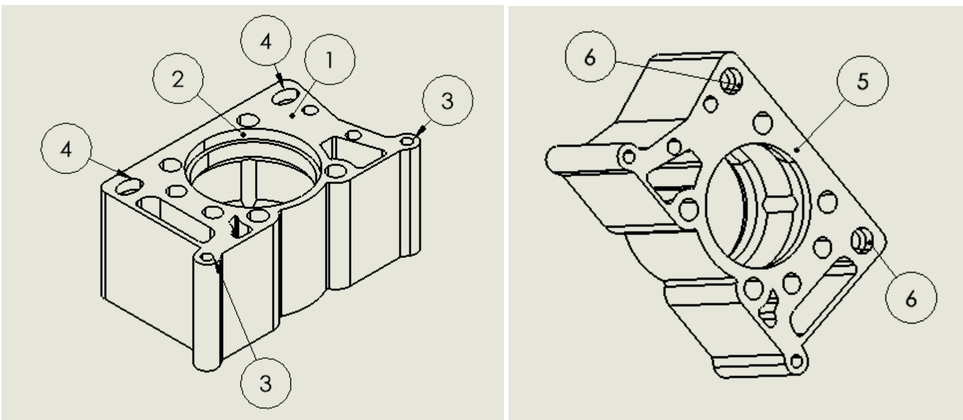


FIGURE 88. MACHINING OPERATIONS

For satisfying the target year production 26 cylinders must be processed per hour, resulting in a relative cycle time for single cylinder equals to 2.33 mins. The relative duration computed with the design cycle is <u>2.07 mins</u>, a satisfy result that allows to use only one workstation.

Considering all, the costs for this department are:

- CNC machine Okuma MU6300V costs 300 000 € with a depreciation of 75 000 € per year. Its consumption corresponds to 13.2 kWh and related maintenance is equal to 21 000 € per year.
- A qualified operator handles the CNC machine with a wage of 23 000 € per year
- Tool carriers' costs are equal to 2250 €
- Tools costs have been evaluated considered the prescribed Seco Tool duration of 30 mins. Starting from the cutting time evaluated in the working cycle, from the overall productive working hour and from the overall cycle duration, it has been possible to evaluate the overall tools consumption and costs quantified in 25100 € per year.

The overall hourly cost is quantified in **48.19 €/h**.

The department costs with respect to a single cylinder block are here reported, the considered production per hour is the target one of 26 cylinders per hour, however, since times smaller have been founded with the presented design, the costs could be also lower, but a safety margin has been kept:

Cost Center	Cutting	€ 0,65
	Pre heating	€ 0,70
	Extrusion	€ 2,06
	Heat treatments	€ 1,41
	Machining	€ 1,87

TABLE 57. DEPARTMENT COSTS FOR A SINGLE CYLINDER PRODUCTION

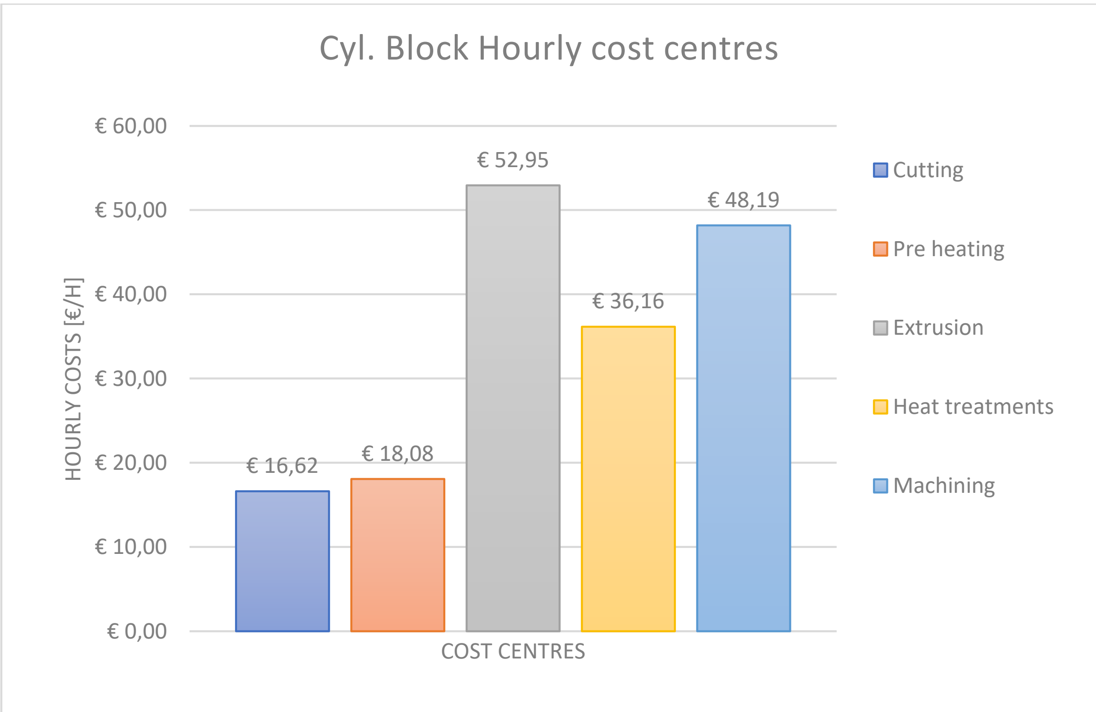


FIGURE 89. CYLINDER BLOCK PRODUCTION DEPARTMENTS HOURLY COSTS

5.5 Crankshaft

The last component analysed during this work has been the crankshaft. This piece is one of the items that make up the “core” of the thermal engine, its purpose is to transform and transmit the piston reciprocating motion into a rotation movement. Moreover, it usually drives the auxiliaries like the distribution transmission, the water pump, the alternator – that in this engine design is not foreseen due to the range extender architecture nature – and some other assemblies like the oil pump.

The architecture designed for this component – as it has already explained during chapter 4 – is an unusual solution, since a mountable crankshaft has been defined. Moreover, counterweights, that are usually carried by cheek in a crankshaft, are incorporated into the main journal. The resulting solution is a very simple shape that, for its nature, allows to exploit connecting rods made in one piece. The union between the five main journals and the four crankpin journal is made by screws and a conical coupling. Moreover, to allow right positioning and centring operations, six metal rings have been foreseen to be mounted on the central main journal in order to lock it in the right centre of the basement.

Below a classical crankshaft solution is compared with the adopted one:

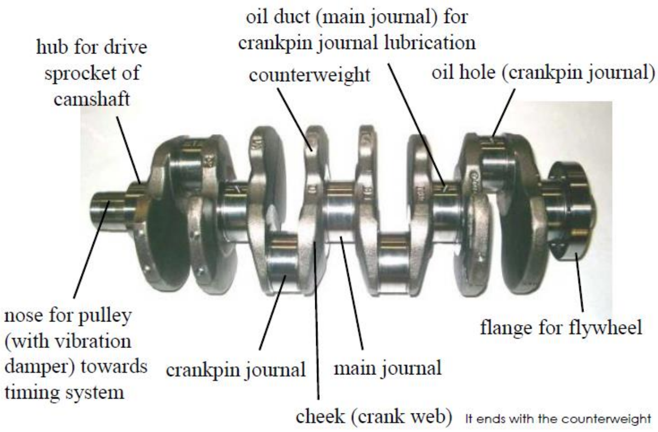


FIGURE 90. EXAMPLE OF WIDESPREAD CASTED CRANKSHAFT SOLUTION
SOURCE: DELPRETE C., "POWERTRAIN COMPONENT DESIGN-04_EL_CRANKSHAFT", TORINO, 2021

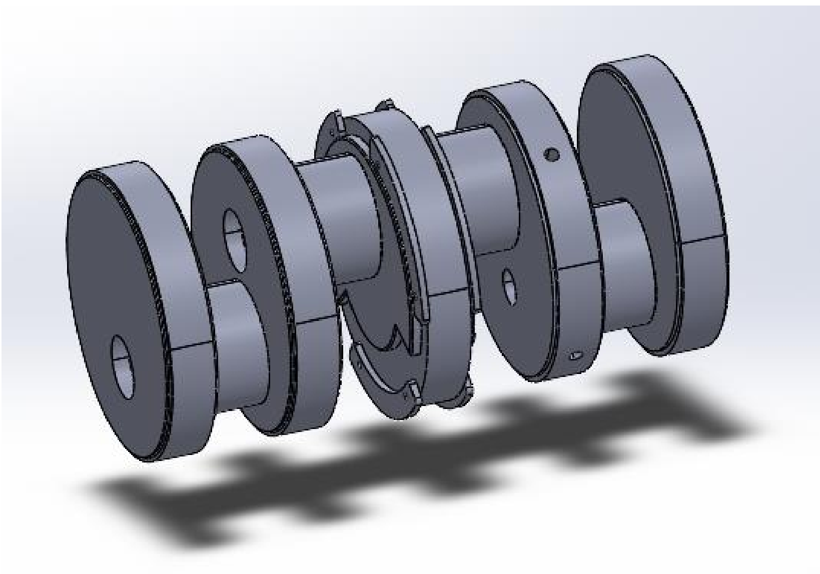


FIGURE 91. THE ADOPTED MOUNTABLE SOLUTION

For what deals with the proper production and cost analysis, the usual procedure will be followed: after this introduction, the material needed for the component's production will be computed together with its related costs. In the subsequent paragraph, instead, the technological transformations will be analyzed with the consequent foreseen expenses.

For the manufacturing organization of the crankshaft assembly, three different processes must be considered respectively for the main journals, the crankpin journals and the ring shoulders. In the first two cases the idea is to start from hot rolled round bars while, for the ring shoulders, a plate has been chosen as starting semi-worked. Then, machining procedures have been designed to get the results.

The material exploited is the same for the three parts and it is a micro alloyed steel – 35MnV7.

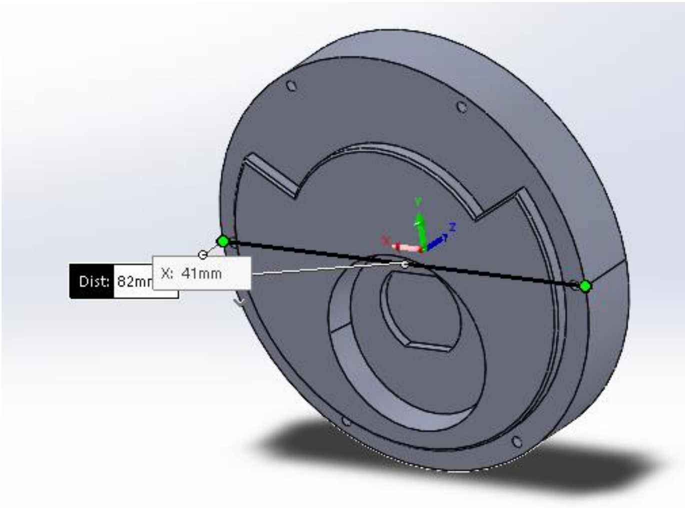


FIGURE 92. CENTRAL MAIN JOURNAL GEOMETRY AND DIMENSIONS

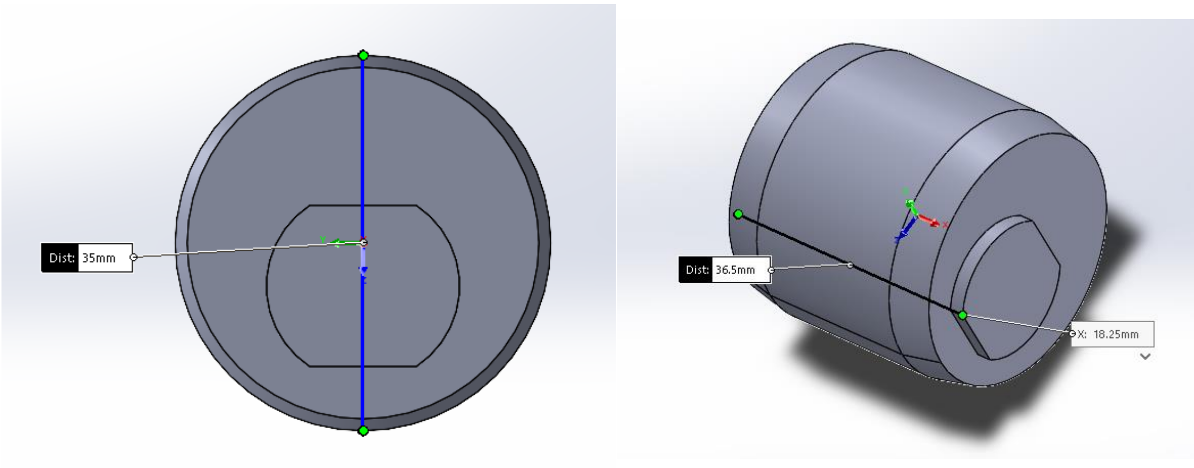


FIGURE 93. CRANKPIN JOURNAL GEOMETRY AND DIMENSIONS

5.5.1 Weight and Cost Material

The presented material is the 35MnV7 steel, it belongs to the micro alloyed steel. This category of material has increased, in the last years, the OEMs' interest since its costs are contained and, with respect to other classical solutions, the expense save is important. Moreover, even if little worse mechanical properties are shown, the performances guaranteed from these materials are respectable and satisfactory.

These steels are produced exploiting low-cost carbon alloy: the precipitations of some compounds like nitrides and carbides have been used to strength the alloy maintaining, at the same time, very good workability peculiarities. The precipitation procedure is normally performed during a deformation, in the plastic field, at a pre-determined temperature.

The cost of this material per kilogram can be evaluated in 1,8 €/kg for both the bars and the plate, the same cost is justified by the semi-worked condition that requires previous operations performed by the suppliers like lamination or peeling.

In this case, the material weight necessary for each part has been computed starting from the CAD dimensions – instead of the usual volume – since the components have been only machined and so, the semi-worked has been the centre of the material consumptions and related costs.

For the main and the crankpin journal, two different diameters bars have been chosen, in particular for the main a bar of 85 mm diameter has been selected while, for the crankpin, a 42 mm diameter bar has been the choice. This decision has been driven by the dimensions of the final components that, respectively, are 82 mm and 35 mm, moreover, the Rodacciai catalogue has been used as reference for the available diameters; each bar has a length of 3 meters. For what deals with the length dimensions of the components 35 mm is the thickness of the main journal while 36.5 mm is the thickness of the crankpin journal.

Having in hand all these data, the amount of material consumed in a year, considering the target yearly production and the quantity of each part per engine – consulting the Bill of Material, could have been computed. The volume and so the weight – considering 7800 kg/m^3 as steel density – of each semi-worked has been computed, then, taking into account the length of the different components, the number of bars needed per year can be pointed out. At this point, the only step to do is to multiply the weight of material needed per year with the unitary cost per kilogram. The results obtained are here reported:

Semi-worked Volume (ϕ 85)	17023505,19	mm^3
Semi-worked Weight	136,11	kg
Semi-worked cost	245,00	€
Bars needed in a year	700	
Material cost per year	171498,60	€
Material cost for a single main journal	1,63	€

TABLE 58. MATERIAL COST FOR MAIN JOURNAL

Semi-worked Volume (ϕ 42)	3402344,844	mm^3
Semi-worked Weight	27,21	kg
Semi-worked cost	48,98	€
Bars needed in a year	1176	
Material cost per year	57598,13	€
Material cost for a single main journal	0,69	€

TABLE 59. MATERIAL COST FOR CRANKPIN JOURNAL

Finally, for what deals with the ring shoulders, a plate with a surface of 1000mmx1000mm and a thickness of 10 mm has been chosen as starting semi-worked to be cut and worked. Considering the dimensions of a ring – 247,55 mm^2 is the surface of each ring – and the target production per year, the number of plates needed in a year can be computed and so the related cost materials:

Semi-worked plate volume	10000000	mm^3
Plate weight	78,00	kg
Plate cost	140,4	€
Ring shoulder per plate	4000	
Plate needed in a year	32	
Material cost per year	4492,8	€
Material cost for a single ring shoulder	0,04	€

TABLE 60. MATERIAL COST FOR RING SHOULDER

Considering these values, for the production of a crankshaft assembly, the expense related to the material purchasing is given by the cost for the single components multiplying for the related quantities that make up the assembly so:

COMPONENT	UNIT COST	QUANTITY	TOTAL
MAIN JOURNAL	€ 1,63	5	€ 8,17
CRANKPIN JOURNAL	€ 0,69	4	€ 2,74
RING SHOULDER	€ 0,04	6	€ 0,21
OVERALL			€ 11,12

TABLE 61. OVERALL MATERIAL COST FOR A SINGLE CRANKSHAFT

However, as for previous components, a little return must be considered for the purchasing of scrap for a quotation of 0.5 €/kg. The scrap amount is calculated considering the difference between the initial dimensions of the semi-worked and the final components.

5.5.2 Manufacturing Processes and Related Costs

The technological procedures designed for the crankshaft's components have been already anticipated, however, here they will be described better, and the related cost analysis will be presented. For what concerns with all the items that make up the crankshaft, the idea, since their shapes are simple and no complicated machining procedures are necessary, is to start from semi-worked manufact to be machined in order to get the final result.

Dealing with the crankpin and the main journal, after the cutting of the initial semi-worked bar, a machining cycle followed by a grinding has been foreseen. Moreover, even if the heat treatment has been already done by the material's supplier, an induction tempering is used for hardening the material.

The ring shoulders, instead, will be, after the semi-worked cut, drilled and milled; then, also in this case, a stress relief treatment has been scheduled.

Induction tempering is a treatment that exploits the heating generated by a variable electromagnetic field. Practically, with this process the portion of material heated is localized and does not involve all the component, this process is far shorter with respect a traditional heat treatment and allows to get a satisfactory surface hardness. For what deals with the process's principle, it can be said that the variable electromagnetic field excites the iron's electrons achieving a sort of self-heating. The deepness of material heated depends on the frequency of the electromagnetic field. Then, when the satisfactory temperature has reached and maintained for the desired time – in the case analysed and for the steel in general the reference is the austenization temperature – a multiple quenching procedure is used. The final result is a component hardened in the localized zone with a very short industrial operating time. For the specific case, the contact surfaces will be mainly the zones interested in the treatment.

A last important notation is that the grinding zone is shared between each of the components. For the cutting and the induction tempering, instead, an area is foreseen for the main journal and crankpin journal production while a dedicated machine is used for the ring shoulders.

5.5.2.1 Main Journal Production process

The main journal production has been divided in the four different steps described above, moreover, the same organization has been thought for the industrial areas.

Consequently, the *first area* is the cutting zone, here the 85 mm diameter bars will be cut in the right length – 35 mm, the thickness of this item – in order to be ready for the machining procedure.

The equipment and personal foreseen for this area are:

- Bekamak's band saw model BMSO-420-XS costs 50 000 € equals to 12 500 € of depreciation per year, its consumption is 18 kWh and its maintenance is 3500 € per year. At this voice also 5166€ per year must be considered for the blade substitution
- An operator handles the saw and he is the responsible of this area with a wage of 20 000 €.

The hourly cost of this department is **20.47 €/h**.

The *second area* is the proper machining workstation, before to point out the cost of this department, the machining operation will be explained, moreover, as it has been usual after the first component treated in this thesis, the working cycle will not be reported to not overload the work of table and to make the discussion more fluent.

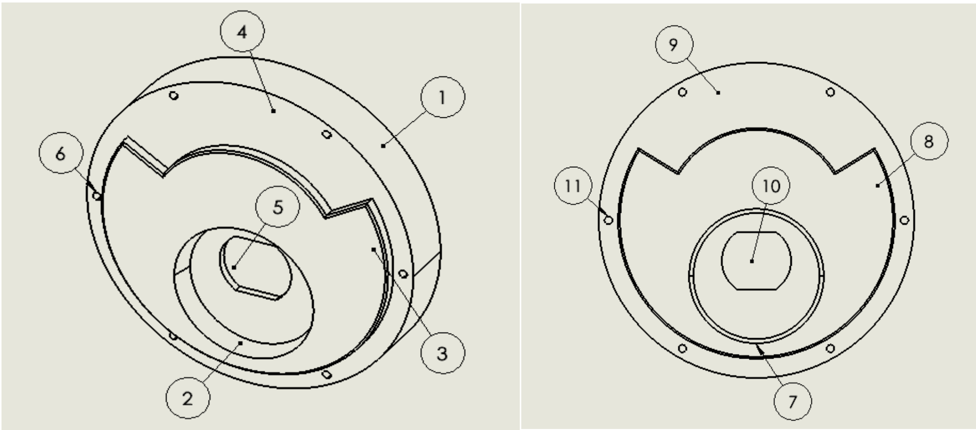


FIGURE 94. MAIN JOURNAL WORKING CYCLE OPERATION

The working operations that have to be done on the main journal will be made exploiting two positioning of the item in the machine, moreover, except the turning operation that has to be performed on the external edge, the other procedures are symmetrical in the two positioning and involves two planar face. The working cycle analysed is the one that deals with the central main journal, since two more operations with respect to the other four main journals have to be performed; this fact set this item as the more time consuming and the more expensive between the five journals.

As it has already said, a turning must be foreseen and it is a very important operation since this surface must be very precise due to the contact with the semi-bushing. If an approximative turning would be done, deterioration, rupture and noise of the bushing are natural consequences that must be avoided. The turning operation is indicated with the number 1 in Figure 94.

The subsequent operations are the milling of the hole for the conical coupling – operation 3 in Figure 94, the milling of the shape coupling – operation 4 in Figure 94 and, last, a turning of the conical surface must be performed. Moreover, the drilling of the holes for the ring shoulder mounting must be done too – operation 6 in Figure 94.

On the other side, during the working procedure in position 2, the same operations will be performed, exception made for the operation 1.

As usual, the times for the operations have been computed considering the cutting parameters provided by Seco Tools and considering the surfaces to be machined. Moreover, this data has also been exploited for the tools wear and consumption in order to get the cost needed for the tools change.

The hourly production request in an hour for reaching the target number of components in a year is of 32 main journals, the computed cycle of 1.8 min for each main journal ensures to get the goal.

Dealing with the equipment, the *second area* is organized in this way:

- DMG Mori NT4200 DCG multi-spindle lathe that costs 120 000€ for a depreciation of 30 000€ per year, its consumption amounts to 36 kWh with a maintenance of 8400 €.
- Tools carriers costs are evaluated in 7500 €
- Tools consumption, instead, is 135 640 € per year.
- A specialized operator is needed with a wage of 23 000 €.

The Overall cost for this area per hour is **63.69 €/h**.

The *third area* is dedicated to the zone of the components' grinding, below the costs have been reported:

- A grinding bench provided by Jiurong Technology ® has been chosen with a related investment of 35 000 €, the depreciation for a year is 8750 €, energy consumption is quantified in 18.9 kWh with a maintenance of 2450 €.

FIGURE 95. JIURONG TECHNOLOGY GRINDING BENCH.

- An operator handles this area with a wage of 20 000 €.

The expenses per hour for this cost center, considering also that this cost is shared with crankpin journal and ring shoulder production, is **18.01 €/h**.

Finally, the *last area* is the one dedicated to the induction tempering treatment, this zone is set in this way:

- An inductor machine provided by Lihua ® has been chosen with an expenses of 10 000 € and a related depreciation of 2500 € per year. The consumption of this machine is 120 kWh and the maintenance is quantified in 500 € per year.

FIGURE 96. LIHUA INDUCTION TEMPERING MACHINE

- A qualified operator is responsible of this zone with a wage of 20 000 €.

The cost of this area per hour is **31.04€/h**.

Now, taking into account that except the machining area all the other cost centres have been shared with the other part, the manufacturing expenses of each main journal in relation to each department can be pointed out.

Cost Center	Cutting	€ 0,35
	Machining	€ 1,98
	Grinding	€ 0,19
	Induction tempering	€ 0,54

TABLE 62. SINGLE MAIN JOURNAL MANUFACTURING PRODUCTION

5.5.2.2 Crankpin Journal production

For the crankpin manufacturing process, since the cutting area, the grinding and the induction tempering have been shared with the main journal, they will not be presented again. Instead, the machining working cycle will be described and the related cost will be pointed out too.

The working cycle designed for the crankpin journal is essentially made by two technological transformation: milling and turning. The positioning exploited have been two, necessary to work both the surfaces shape coupled with the main journal. For what deals with the operations, it must be absolutely necessary the turning of the external cylindrical surface – indicated with number 1 in Figure 97– in order to ensure a perfect coupling with the connecting rod big eye surface. Moreover, when the border edges will be reached, the conical surfaces for the coupling must be performed. Dealing, instead, with the planar surfaces, a milling operation are needed in order to ensure the right dimensions for the shape coupling – operations number 2 and 3 and operation 4 and 5 for the positioning 2. The required production to reach the annual target is 26 crankpin journals machined per hour, with a computed cycle duration of 2.12 min 28 crankpin journals can be produced in an hour.

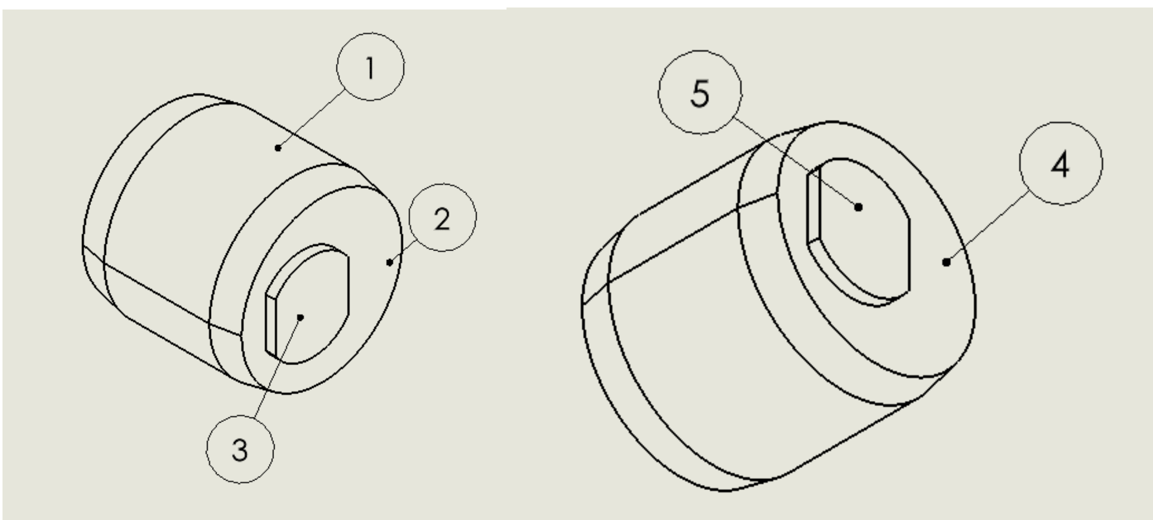


FIGURE 97. CRANKPING JOURNAL WORKING CYCLE OPERATIONS

The equipment required for this department is pretty the same designed for the main journal production, machining cost centre. However, tools costs are obviously changed:

- DMG Mori NT4200 DCG multi-spindle lathe that costs 120 000€ for a depreciation of 30 000€ per year, its consumption amounts to 36 kWh with a maintenance of 8400 €.
- Tools carriers costs are evaluated in 7500 €
- Tools consumption, instead, is 32 057 € per year.
- A specialized operator is needed with a wage of 23 000 €.

The Overall cost for this area per hour is **36.72 €/h**.

Considering the other hourly cost centers from the results presented for the main journal production, the manufacturing cost for a single crankpin journal are:

Cost Center	Cutting	€ 0,35
	Machining	€ 1,43
	Grinding	€ 0,19
	Induction tempering	€ 0,54

TABLE 63. SINGLE CRANKPIN JOURNAL MANUFACTURING COST

5.5.4.3 Ring shoulders production

This component's working cycle production is quite different with respect to the previous crankshaft's parts presented that, by opposite, are quite similar under the manufacturing process point of view.

The ring shoulders are indeed produced starting from a plate, this results in a different choice of machinery, moreover, since a different shape and a very simple machining working cycle must be performed, only the grinding step will be shared with the journals.

The *first cutting area*, in this case, has been thought to be equipped with a quite different saw type, for this kind of application, a laser type saw is far more suitable and it is a smarter choice because it is very precise and for the plate cutting is very useful.

The equipment foreseen for this area is:

- An automatic laser saw has been chosen for an investment of 30 000 € that turns into a depreciation of 7 500 € per year. Its consumption is 12 kWh and its maintenance is equal to 2100 € per year.

FIGURE 98. AUTOMATIC LASER SAW

- An operator handles this machine with a wage of 20 000 €.

The hourly cost of this department is **16.55 €/h**.

The machining area is equipped with a drill press for the hole making and with a CN milling machine for the milling of the surfaces.

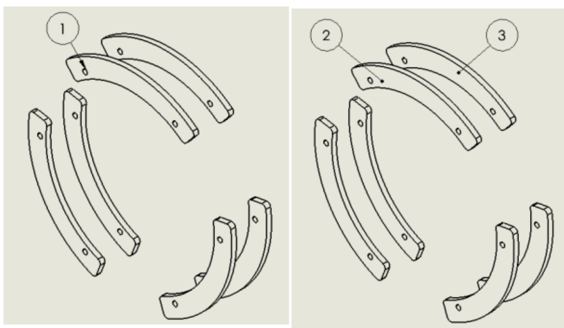


FIGURE 99. RING SHOULDERS MACHINING STEP

The related costs are:

- 3000 € for the drill press with a depreciation of 750 € per year. Its consumption is 1.32 kWh and its maintenance corresponds to 210 € per year.
- 500 € are foreseen for the drill bits.
- An operator with a wage of 20 000 € is the responsible of this area
- A CN milling machine provided by FirmCNC model FM6060 for a cost of 6500 € with a depreciation per year of 1625 €. Its consumption is 6,6 kWh and its maintenance amounts to 455 € per year.

FIGURE 100. CNC MILLING MACHINE FOR RING SHOULDERS

- Tools and tools carrier costs are quantified in 1300 € per year.

The total hourly cost for the machining cost center is **21.53 €/h**.

Finally, since the grinding workstation is shared with the journals, the tempering process is analyzed. In this case, since smaller dimensions must be handled and also a smaller number of items per year must be processed, a smaller machine has been chosen with respect to the one selected for the journal resulting in lower related costs:

- An inductor machine provided by Lanshuo ® model bs has been chosen with an expense of 3500 € and a related depreciation of 875 € per year. The consumption of this machine is 60 kWh and the maintenance is quantified in 175 € per year.

FIGURE 101. LANSHUO INDUCTION HARDENING MACHINE

- A qualified operator is responsible of this zone with a wage of 20 000 €.

The cost of this area per hour is **21.53€/h**.

Now, taking into account the evaluated hourly cost and considering the value founded for the main and crankpin journal grinding area – since it is shared with those items – the manufacturing cost for a single ring shoulder can be pointed out.

Cost Center	Cutting	€ 0,50
	Machining	€ 0,82
	Grinding	€ 0,19
	Induction tempering	€ 0,56

TABLE 64. SINGLE RING SHOULDER MANUFACTURING PRODUCTION

6. Results

In this chapter, the overall cost to produce each of the components analysed in the work will be reported; moreover, other interesting results useful for pointing out some conclusions and considerations will be copied too.

6.1 Cylinder Head production overall cost

Cylinder head assembly, as it has been explained, is one of the most stressed components of an internal combustion engine, its production procedure and the material's choice is of paramount importance. Moreover, since a material that shows high mechanical peculiarities, good thermal resistance and good corrosion characteristics is needed, the related material's costs could be important; however, a satisfactory design has been obtained considering the stainless steel presented. In addition, a quite complex machining procedure could raise manufacturing costs.

Considering those facts, an overall acceptable cost expected to produce one head with fixed element is included between 50 € and 75 €.

The cost obtained in this analysis shows that the industrial design carried out is feasible, under an economical point of view, for the year target production:

	€/HEAD WITH FIXED ELEMENT	
MATERIAL	Steel 17-4 ph	€ 21,39
	Wax	€ 0,54
	Ceramic shell material	€ 3,50
COST CENTER	Wax bunch production	€ 3,82
	Ceramic shell prod. and dewaxing	€ 5,04
	Melting and shell removal	€ 6,97
	Cutting and grinding	€ 2,39
	Heat treatments	€ 1,91
	Machining	€ 10,52
	Valve seat and guide installation and machining	€ 4,16
	Total	**€ 60,25**

TABLE 65. FINAL COST FOR HEAD WITH FIXED ELEMENT PRODUCTION

6.2 Turbocharger assembly production cost

Dealing with the turbocharger assembly, a more complex discussion must be performed, indeed, the high number of parts and the important differences among them make toughest the speech.

For this reason, the cost to produce each single part is reported and, finally, the total expenses foresee for the turbocharger's components manufacturing will be ruled out. In general, some of these components have to handle the very high temperature of residual gases coupled with an important fatigue stress – where the part considered is thought to overcome a rotating movement. This background forces to use some very expensive materials – like the one chosen for the turbine turbomachine – resulting in an important cost's voice in the final production disbursement.

The tables that summarize the costs for the production of each part are reported:

		€/COMPRESSORS' STAGE
MATERIAL	ASTM 2014	€ 0,01
	Ceramic shell	€ 0,33
	Wax	€ 0,00
COST CENTER	Wax Bunch production	€ 0,34
	Ceramic shell production	€ 0,37
	Melting & shell removal	€ 0,35
	Cutting and grinding	€ 0,21
	Heat treatments	€ 0,11
	Machining	€ 0,97
	Total	**€ 2,70**
	Total cost for 22 rotors and 22 stators for three compressors per turbocharger	**€ 118,80**

TABLE 66. COMPRESSORS' STAGES PRODUCTION COST

		€/TUBINE'S CSMX-4 ® STAGES
MATERIAL	CSMX4	€ 10,49
	Ceramic shell	€ 0,31
	Wax	€ 0,01
COST CENTER	Wax Bunch production	€ 1,00
	Ceramic shell production	€ 1,10
	Melting	€ 1,00
	Shell Removal	€ 0,40
	Cutting and grinding	€ 0,47
	Heat treatments	€ 0,72
	Machining	€ 3,47
	Total	**€ 18,96**

	Total cost for stators and rotors of 1st and 2nd two turbine stages	**€ 75,85**

TABLE 67. CSMX-4 ® TURBINE'S STAGE PRODUCTION COST

		€/WASPALOY TURBINE'S STAGES
MATERIAL	Waspaloy	€ 8,18
	Ceramic shell	€ 0,31
	Wax	€ 0,00
COST CENTER	Wax Bunch production	€ 1,00
	Ceramic shell production	€ 1,10
	Melting	€ 1,25
	Shell Removal	€ 0,40
	Cutting and grinding	€ 0,47
	Heat treatments	€ 0,72
	Machining	€ 3,47
	Total	**€ 16,90**
	Total cost for stators and rotors of 3rd and 4th turbine stages	**€ 67,61**

TABLE 68. WASPALOY ® TURBINE'S STAGE PRODUCTION COST

		€/TI-SF61 TURBINE'S ROTOR
MATERIAL	Ti-SF61	€ 0,76
	Ceramic shell	€ 0,31
	Wax	€ 0,00
COST CENTER	Wax Bunch production	€ 1,00
	Ceramic shell production	€ 1,38
	Melting	€ 1,66
	Shell removal	€ 0,40
	Cutting and grinding	€ 0,47
	Heat treatments	€ 0,96
	Machining	€ 3,47
	Total	**€ 10,42**
	Total cost for rotors of 5th,6th and 7th turbine stages	**€ 31,26**

TABLE 69. TI-SF61 TURBINE'S ROTOR PRODUCTION COST

	€/ UNS S30815 TURBINE'S STATOR	
MATERIAL	UNS S30815	€ 0,32
	Ceramic shell	€ 0,31
	Wax	€ 0,01
COST CENTER	Wax Bunch production	€ 1,00
	Ceramic shell production	€ 1,10
	Melting	€ 1,25
	Shell removal	€ 0,40
	Cutting and grinding	€ 0,47
	Heat treatments	€ 0,96
	Machining	€ 3,47
	Total	**€ 9,28**
	Total cost for stators of 5th,6th and 7th turbine stages	**€ 27,85**

TABLE 70. UNS S30815 TURBINE'S STATORS PRODUCTION

After the compressors' and turbine's stages production, the spiral diffusers costs are reported:

	€/ASTM 2014 COMPONENTS	
MATERIAL	ASTM 2014	€ 0,76
	Ceramic shell	€ 1,02
	Wax	€ 0,12
COST CENTER	Wax Bunch production	€ 1,56
	Ceramic shell production	€ 1,75
	Melting & shell removal	€ 0,10
	Cutting and grinding	€ 1,03
	Heat treatments	€ 1,05
	Machining	€ 1,57
	Total	**€ 8,96**
	Total cost for five compressors' spiral diffuser and support flange per turbocharger	**€ 62,71**

TABLE 71. COMPRESSORS' SPIRAL DIFFUSERS PRODUCTION COSTS

	€/TURBINE SPIRAL DIFFUSER	
MATERIAL	CSMX4	€ 344,40
	Ceramic shell	€ 1,02
	Wax	€ 0,12
COST CENTER	Wax Bunch production	€ 1,56
	Ceramic shell production	€ 1,75
	Melting & shell removal	€ 1,00
	Cutting and grinding	€ 1,03
	Heat treatments	€ 5,27
	Machining	€ 1,57
	Total	**€ 357,71**
	Total cost for a turbine spiral diffuser per turbocharger	**€ 357,71**

TABLE 72. TURBINE'S SPIRAL DIFFUSER PRODUCTION COST

As it can be seen, the cost for the turbine's spiral diffuser is very high due to its high weight and so material requirement. This aspect will be treated in the conclusion chapter.

Now, the costs for the turbine's diffuser and for the cases, both produced in stainless steel UNS S30815, are provided:

	€/TURBINE 'S DIFFUSER INTERNAL ITEM	
MATERIAL	UNS S30815	€ 0,40
	Ceramic shell	€ 1,02
	Wax	€ 0,12
COST CENTER	Wax Bunch production	€ 1,56
	Ceramic shell production	€ 1,75
	Melting & shell removal	€ 1,25
	Cutting and grinding	€ 1,03
	Heat treatments	€ 5,27
	Machining	€ 1,57
	Total	**€ 13,97**
	Total cost for five spiral diffuser per turbocharger	**€ 13,97**

TABLE 73. INTERNAL TURBINE'S DIFFUSER ITEM PRODUCTION COST

	€/TURBINE'S DIFFUSER EXTERNAL ITEM	
MATERIAL	UNS S30815	€ 1,34
COST CENTER	Cutting	€ 0,75
	Welding	€ 2,53
	Folding	€ 3,51
	Machining	€ 4,55
	Total	**€ 12,68**

TABLE 74.EXTERNAL TURBINE'S DIFFUSER ITEM PRODUCTION COST

	€/CASE	
MATERIAL	UNS S30815	€ 15,68
COST CENTER	Cutting	€ 0,75
	Machining	€ 4,55
	Total	**€ 20,98**

TABLE 75. TURBOMACHINES' CASES PRODUCTION COSTS

Finally, the turboshaft production costs are reported:

	€/TURBOSHAFT	
MATERIAL	20 MnCr 5	€ 0,36
	Scrap purchasing (-)	€ 0,03
COST CENTER	Cutting and grinding	€ 4,28
	Machining C1 e C2	€ 7,62
	Machining EM	€ 6,15
	Machining C3 e T	€ 7,89
	Total	**€ 26,26**

TABLE 76. TURBOSHAFT PRODUCTION COSTS

Considering all the cost to produce each single part, the overall cost for the manufacturing of a turbocharger assembly, without the assembly costs, can be summarized in a table to have a clearer idea.

Component	Cost/unit estimated	Weight [%]	Quantity	Total	
Turbine's spiral diffuser	€ 357,71	40,71%	1	€ 357,71	
Stator/rotor turbine's stages					
CSMX4	€ 18,96	23,06%	4	€ 75,85	€ 202,57
Waspaloy	€ 16,90		4	€ 67,61	
Ti-SF61	€ 10,42		3	€ 31,26	
UNS S30815	€ 9,28		3	€ 27,85	
Stator/rotor compressors' stages	€ 2,70	13,52%	44	€ 118,80	
Cases	€ 20,98	9,55%	4	€ 83,92	
Compressors' spiral diffusers	€ 8,96	5,10%	5	€ 44,79	
Turbine's diffuser	€ 26,64	3,03%	1	€ 26,64	
Turboshaft	€ 26,26	2,99%	1	€ 26,26	
Support flange	€ 8,96	2,04%	2	€ 17,92	
				€ 878,62	

TABLE 77. TURBOCHARGER ASSEMBLY OVERALL COSTS

From this table it can be seen the total cost for the production of a turbocharger, the final expense founded is very high and it is mainly caused by the turbine’s diffuser spiral cost. Its production is very expensive and the most important cause is its cost as it can be seen in Table 72. This fact sets this component to be reviewed in future in order to overcome this problem and make its production feasible.

6.3 Basement assembly production cost

In this paragraph, the overall costs for the elements that make up the basement assembly will be reported; moreover, also the extrusion cost per kilogram will be pointed out, since a value included between 5€/kg and 10€/kg is expected to be founded for a well design process.

		€/BASEMENT
MATERIAL	Material	€ 27,04
	Scrap purchasing (-)	€ 2,14
COST CENTER	Cutting	€ 4,19
	Pre heating	€ 2,39
	Extrusion	€ 13,33
	Heat treatments	€ 4,79
	Machining	€ 10,18
	Total	**€ 59,78**

TABLE 78. BASEMENT ELEMENT PRODUCTION COST

The extrusion process cost – that is composed by the cost of the zones that make up the extrusion, so the cutting, preheating, extrusion and heat treatments departments, and by the materials' costs divided for the component's weight – is equal to 3.85 €/kg.

		€/CYLINDER BLOCK
MATERIAL	Material	€ 1,40
	Scrap purchasing (-)	€ 0,11
	Cutting	€ 0,65
	Pre heating	€ 0,70
COST CENTER	Extrusion	€ 2,06
	Heat treatments	€ 1,41
	Machining	€ 1,87
	Total	**€ 7,98**
	Total for 4 cylinder (1 engine)	**€ 31,91**

TABLE 79. CYLINDER BLOCK PRODUCTION COSTS

Also in this case, the extrusion cost per kilogram is reported and it corresponds to 9.16 €/kg, this time this value is quite high since the weight of a single component is very restrained. However, it is still acceptable and satisfactory.

6.4 Crankshaft production costs

At last, the final costs for the crankshaft production are reported. Such a component has to be hard enough to overcome important contact stresses and a very high number of fatigue cycle, for this reason the induction tempering hardening has been foreseen with not negligible industrial's costs. However, the final 50€ for the production of a crankshaft is a good result that makes feasible the process designed and validates the structural design previously performed.

	€/MAIN JOURNAL	
MATERIAL	Material	€ 1,63
	Scrap purchasing (-)	€ 0,15
COST CENTER	Cutting	€ 0,35
	Machining	€ 1,98
	Grinding	€ 0,19
	Induction tempering	€ 0,54
	Total	**€ 4,53**
	Total for 5 main journal (1 crankshaft)	**€ 22,67**

TABLE 80. TOTAL COST FOR MAIN JOURNAL PRODUCTION

	€/CRANKPIN JOURNAL	
MATERIAL	Material	€ 0,69
	Scrap purchasing (-)	€ 0,02
COST CENTER	Cutting	€ 0,35
	Machining	€ 1,43
	Grinding	€ 0,19
	Induction tempering	€ 0,54
	Total	**€ 3,16**
	Total for 4 crankpin journal (1 crankshaft)	**€ 12,66**

TABLE 81. TOTAL COSTS FOR CRANKPIN JOURNAL PRODUCTIONS

	€/RING SHOULDER	
MATERIAL	Material	€ 0,04
	Scrap purchasing (-)	€ 0,00
COST CENTER	Cutting	€ 0,50
	Drilling and milling	€ 0,82
	Grinding	€ 0,19
	Induction tempering	€ 0,56
	Total	**€ 2,11**
	Total for 6 ring shoulder (1 Crankshaft)	**€ 12,63**

TABLE 82. TOTAL COSTS FOR RING SHOULDERS PRODUCTION

Summing up the cost of parts' production necessary to make up a single crankshaft, the final cost for the production of this piece is 47,96 €, that is, also in this case, an acceptable cost and a satisfactory result for the industrial process and material choice design.

Finally, all the result obtained in this work have been grouped and reported in a single table in order to introduce what this six months work have produced.

Group	Element	Unit cost	Quantity	Total cost/engine	Group cost/engine
Head with fixed elements	Head Element	€ 56,09	4	€ 224,36	**€ 241,00**
	Fixed elements	€ 4,16	4	€ 16,64	
Turbocharger	Turbine's spiral diffuser	€ 357,71	1	€ 357,71	**€ 878,62**
	Stator/rotor turbine's stages	€ 202,57	1	€ 202,57	
	Stator/rotor compressors' stages	€ 2,70	44	€ 118,80	
	Cases	€ 20,98	4	€ 83,92	
	Compressors' spiral diffusers	€ 8,96	5	€ 44,80	
	Turbine's diffuser	€ 26,64	1	€ 26,64	
	Turboshaft	€ 26,26	1	€ 26,26	
	Support flange	€ 8,96	2	€ 17,92	
Basement	Basement element	€ 59,78	1	€ 59,78	**€ 91,69**
	Cylinder block	€ 7,98	4	€ 31,91	
Crankshaft	Crankweb	€ 4,53	5	€ 22,67	**€ 47,96**
	Crankpin	€ 3,16	4	€ 12,66	
	Ring shoulder	€ 2,11	6	€ 12,63	

TABLE 83. FINAL WORK COST SUMMARY

7. Conclusions

The main topic of this master thesis is the work performed in collaboration with Leonardo Engineers for Integration S.r.l., the subject is the range extender architecture projected and developed previously by other Politecnico di Torino students and the company. Since the main calculations and design procedures have been already implemented, the main target of the last six months has been the study of some components' production methods and the related costs involved.

In conclusion, analysing what it has been obtained, all the results gained are appreciable and satisfactory, however, a separate discussion must be done about the turbocharger assembly final foreseen expenses.

The main worrying aspect is the turbine's spiral diffuser – highlighted in the assembly model of Figure 102 in the red cycle – cost that is equal to 357.71 €.

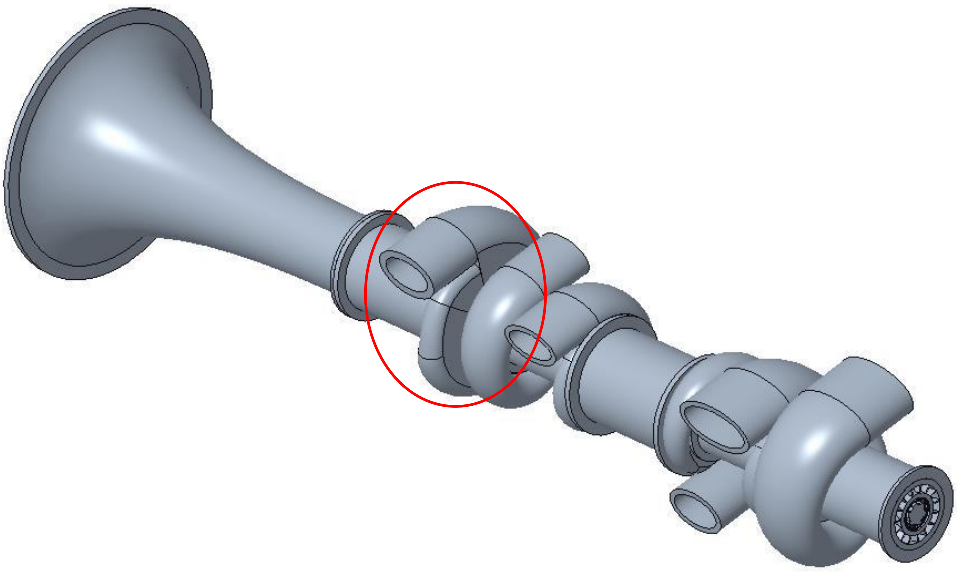


FIGURE 102. TURBINE'S SPIRAL DIFFUSER IN TURBOCHARGER ASSEMBLY

This unexpected cost is mainly driven by the material designed for this component, indeed, since it has to face with the residual gas as soon as they exit from the exhaust manifold, it has to resist to very high temperature, so the material chosen – the Nickel superalloy CSMX-4® - shows very good peculiarities, under this point of view, at the expenses of the costs. Moreover, since this part has an important volume and weight, the amount of money needed only for the material constitutes the almost totality of the costs. So, the production process has not been under investigation while the material chosen has been analyzed and the needed for another raw to be exploited appeared to be unavoidable. The idea is to use a more economic material – that in return could not guarantee the same exercise temperature – to be refrigerated by some air spilled out from compressors, this solution should ensure that the component works at a right lower temperature with respect to the residual gases one.

Future works must include the cost analysis of the remaining engine's components and also all the mounting procedures cost must be carefully analyzed and pointed out in order to evaluate the feasibility of the project and to understand if other weak points – like the turbine's spiral diffuser material – are present.

Moreover, also a deeper new design of the turbine's spiral diffuser must be led in order to implement the solution proposed above.

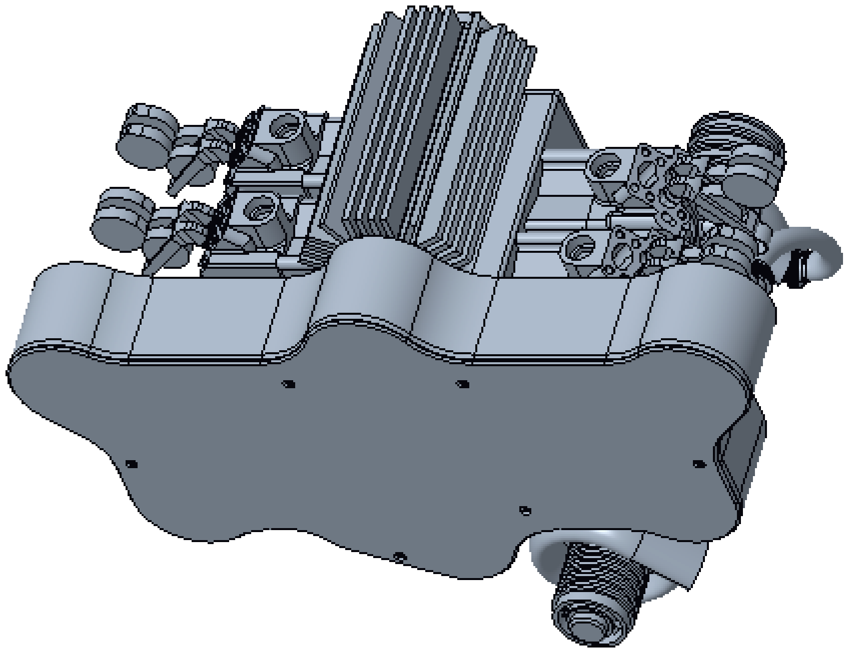


FIGURE 103. THE INTERNAL COMBUSTION ENGINE OBJECT OF THIS WORK

Bibliography

[1] https://www.qualenergia.it/articoli/clima-2020-chiude-il-decennio-piu-caldo-di-sempre/

[2] https://www.qualenergia.it/articoli/clima-2020-chiude-il-decennio-piu-caldo-di-sempre/

[3] Millo F., "Engine emissions control-01. INTRODUCTION_emissions-2020", Torino 2020

[4] Millo F., "Engine emissions control- 05. GASOLINE-FUTURE-DEVELOP", Torino 2020

[5] Spessa E., "Design of engine and control system- L01. TechRM4RV", Torino 2020

[6] Ravello V., "Electric and hybrid propulsion system- Lecture 3", Torino 2020

[7] Ravello V., "Electric and hybrid propulsion system- Lecture 4", Torino 2020

[8] Ravello V., "Electric and hybrid propulsion system- Lecture 13", Torino 2020

[9] Ravello V., "Electric and hybrid propulsion system- Lecture 15", Torino 2020

[10] Ravello V., "Electric and hybrid propulsion system- Lecture 16", Torino 2020

[11] Heywood J.B., "Internal combustion engine fundamentals" McGraw-Hill Education (Professional), 2nd edition, 2019

[12] Ferguson C.R., Kirkpatrick A.T., "Internal Combustion Engines", John Wiley & Sons, 3rd edition, 2015

[13] Garrett T.K., Newton K., Steeds W., "The Motor Vehicle", 13th edition, Butterworth-Heinemann, 2001

[14] Basshuyse R., Schäfer, "Internal Combustion Engine Handbook - Basics, Components, System, and Perspectives", SAE international, 2nd edition, 2016

[15] Genta G., Morello L., "The automotive chassis Volume 2: system design", Springer, 2009

[16] D'Ambrosio S., "Combustion engine and their application to vehicle-Supercharging and Turbocharging", Torino 2020

[17] Catania E. A., "Turbocompressori- Appunti dai corsi seminariali di Vercelli"

[18] Pochini A., "Design and virtual validation of a turbocharger for an internal combustion engine in a range extender application", Torino 2021

[19] Yang, Z., Miganakallu Narasimhamurthy, N., Miller, T., and Naber, J., "Investigation and Optimization of Cam Actuation of an Over-Expanded Atkinson Cycle Spark-Ignited Engine," SAE Int. J. Adv. & Curr. Prac. in Mobility 1(2):639-653, 2019

[20] Luisi, S., Doria, V., Stroppiana, A., Millo, F. et al., "Experimental Investigation on Early and Late Intake Valve Closures for Knock Mitigation through Miller Cycle in a Downsized Turbocharged Engine," SAE Technical Paper 2015-01-0760, 2015

[21] Fabbri R., Kokeny A., "Analisi del prodotto 5 passi per l'innovazione e la riduzione dei costi", FrancoAngeli, 2015

[22] Desai A., Mital A., " Production Economics Evaluating costs of operations in manufacturing and service industry", CRC press

[23] Liu M., Lai J., Shen W.,"A method for transformation of engineering bill of materials to maintenance bill of materials", Robotics and Computer-Integrated Manufacturing Volume 30, Issue 2, April 2014

[24] Atzeni E., "Tecnologia Meccanica- 09 Fonderia (forma transitoria)", Torino 2019

[25] HTTPS://ENGINEERINGPRODUCTDESIGN.COM/KNOWLEDGE-BASE/INVESTMENT-CASTING/

[26] Frezza P., "Concept Development of a Titanium Piston for High Performance Engine", Torino, 2016

[27] https://www.metaltek.com/blog/what-is-investment-casting-and-how-does-it-work/

[28] https://engineeringproductdesign.com/knowledge-base/how-investment-casting-works/

[29] De Virgilio M.R., "Design and FE Analysis of a Cylinder Head for High BMEP ICE for Range Extender Application", Torino, 2017

[30] Ubertalli G., "Tecnologia dei Materiali Metallici", Torino, 2017

[31] https://www.beam-it.eu/Beamit/PDF/Stainless_Steel_17-4_PH.pdf

[32] https://www.uddeholm.com/italy/it/products/uddeholm-vanadis-23-superclean/

[33] Van Liden J.H. Reavis H.G., "Melt Loss Evaluation", Light Metals, 1986

[34] Delprete C., "Powertrain Component Design- Engine Lecture, Cylinder Head", Torino, 2020

[36] Pochini A., "Design and Virtual Validation of a Turbocharger for an Internal Combustion Engine in a range extender application", Torino, 2021

[35] https://matmatch.com/materials/minfm15979-astm-b241-grade-2014-t62

[36] Harris K., Wahl J.B., " IMPROVED SINGLE CRYSTAL SUPERALLOYS, CMSX-4(SLS)[La+Y] and CMSX-4", Muskegon, 2004

[37] https://www.neonickel.com/it/alloys/leghe-di-nichel/waspaloy/

[38] http://www.rettacciai.it/acciai/ita/acciai-cementazione.html

[39] Delprete C., "Powertrain Component Design- Engine Lecture, Thermo-mechanical fatigue", Torino, 2021

[40] Zampini S., "Progettazione del basamento, del sistema di distribuzione e di componentistica di un motore ibrido range extender a ciclo Miller altamente sovralimentato", Torino, 2020

[41] https://www.siderval.it/estrusione-a-caldo/

[42] Atzeni E., "Tecnologia Meccanica-12 Deformazione Plastica", Torino, 2019

[43] Kalpakjian S., Schmid S.R., "Tecnologia Meccanica", Pearson, 2008