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POLYMER INJECTION MOULDING FOR
SHOE SOLES PRODUCTION

Master Degree Thesis

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Escola Tècnica Industrial d'Enginyeria Industrial de Barcelona

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The Academic Reference to MSc Thesis of Lidia Cabanillas López:

This thesis is a work example of a professional and mature R&D engineering. This is a contemporary R&D which fully covers the entire novel project and the industrial production could be started at will.

The thesis in best reviews the details of the economic viability, the product highest standard assurance, the injection mould design as well as it covers the advanced topic of the injection moulding parameters.

Academic Supervisor
Dr G Šmelin
Resumen

Éste es un proyecto de Investigación y Desarrollo (I&D) para la creación de una nueva línea de producción de suelas de zapatos en la comunidad autónoma de Valencia, dónde se concentra dos tercios de la industria española del calzado.

Primero, han sido estudiados las propiedades de los polímeros y se ha profundizado en el estudio de dos tipos distintos: poliolefinas y poliuretanos, los cuales pueden ser fácilmente procesados por moldeo por inyección. Finalmente se ha optado por el poliuretano termoplástico ya que presenta claramente las propiedades mecánicas requeridas para una buena suela de zapato, tales como alta resistencia al impacto, a la abrasión. Además tiene muy buena resistencia al ataque de ácidos, álcalis, agua dulce y salada, hidrocarburos, etc.

Después de haber hecho un estudio de mercado, se ha elegido una estrategia de diferenciación. Esto se conseguirá ofreciendo una gran variedad de colores en las suelas de zapatos.

A continuación, se ha hecho el estudio de viabilidad económica de este proyecto. La inversión necesaria para empezar la producción es de 231745,44 €, la cual se recuperaría al cabo de 9 meses y los beneficios anuales serían de 124509,66 €. También se ha estudiado la posibilidad de producir doble jornada laboral (día y noche). En este caso la inversión inicial aumentaría hasta 387107,91€ pero sería recuperada en tan solo 5 meses y los beneficios anuales aumentarían un 84%, siendo la cifra total de 229784,7€.

Las suelas han sido diseñadas en Solidworks (DAO), así como los moldes para la inyección del poliuretano. Además gracias a esta herramienta se ha podido simular las el peso de un persona y se ha comprobado que el material ofrece la resistencia y flexibilidad necesaria para un calzado cómodo.

Finalmente, se ha simulado sobre los moldes las fuerzas de cierre calculadas en el apartado de cálculos mecánicos, y se ha verificado que los moldes de aluminio son suficientes resistentes para soportarlas.
Abstract

This thesis contains an example of an industrial Research and Development (R&D) project in order to start a new line for shoe soles production in Spain, more specifically in the Community of Valencia, because there is concentrated two thirds of the national footwear industry.

Firstly, the suitable material candidates which specifically fit the production requirements were discussed. In order to choose the right one, a couple of different polymers have been considered: polyolefins and/or polyurethanes.

Secondly, an economical study has been made to review the feasibility of the project. Besides, after making the market analysis a strategy of differentiation has been chosen in order to enter the shoes’ market successfully.

The project also contains the design of the soles and the aluminium moulds. These mechanical designs have been modelled and tested within Solidworks tool. Thanks to this CAD software, the essential mechanical results calculated for this product has been simulated.
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I. Introduction

Shoes are a basic need for the human beings. It is considered as part of the body safety that protects the human body from the adversities, jointly with the clothes and the house. They were originally used to protect feet from harsh temperatures and rough land. Body safety belongs to second level of the Maslow’s Hierarchy of Needs. Maslow’s theory proposed that the lower levels must to be met before the individual will strongly desire the secondary or higher level needs.

![Figure 1 - Maslow's Hierarchy of Needs](image)

Many ancient civilisations, such Romans, already wore ornamental footwear, while durable shoes are a relatively recent invention. The oldest shoes that are known are Egyptian sandals made of palm fibre, and the first leather sandals were found in the bath of Tutankhamen. The Romans considered clothing and footwear as a sign of power. More of them wore footwear, while slaves and peasants remained barefoot. In the Middle Ages the use of high-heeled shoes raised, and there were also associated with power. Nevertheless, bare feet are also seen as a sign of humility and respect. In some cultures, people remove their shoes before entering a home or holy buildings, such as temples [1].

The quantity production started at the end of the XIX century in US and UK. After the Second World War a lot of European countries followed the production model of UK. In the next picture a six-year-old Austrian boy “Werfel” can be seen receiving a new pair of shoes at the Am Himmel orphanage, donated by the Junior Red Cross in America. The photo shows his immense joy to receive a new pair of shoes as a birthday gift.
The sole of the shoes is the part that it is in contact with the floor; hence it is usually made of a tougher material. In the beginnings, the soles were made by esparto or leather, but when the shoes started to be produced in big quantities, plastics started to be used because they reduced the cost and improve properties.

The first man-made plastic was created in 1860 by Alexander Parkes. The material was called Parkesine and was an organic material derived from cellulose that once heated could be moulded, and retained its shape when it was cooled. Nonetheless, in 1939 Charles Goodyear already invented a method to process Natural Rubber and Eduard Simon discovered polystyrene. Plastics started to replace traditional materials, such glass, paper or metals in the second part of the XX century due to their advanced properties and nowadays the use of plastic materials is higher than the metals. The mostly used plastics are the polyolefins, they are used in a wide range of products.

One big advantage of the plastics is that they can be easily processed by increasing the temperature and give them the desired shape by putting them into a mould, once the material is cooled they keep the shape. The most famous plastic processing techniques are: laminate, injection, extrusion, pressing, blowing and rolling.
II. Literature Review

1. Polymers

A polymer is a large molecule composed of many repeated subunits, called monomers. The union of these monomers forms large chains.

As consequence of the union of many such monomers the resulting molecule is significantly larger in comparison to a small molecule, and it produces unique physical properties including toughness, viscoelasticity and a tendency to form glasses and semi crystalline structures rather than crystals.

A variety of natural polymers exists in the nature such as shellac, amber, wool, silk, natural rubber, cellulose, proteins, DNA, etc. Others are synthesize in the laboratory (plastics) such as synthetic rubber, phenol formaldehyde resin (Bakelite), neoprene, nylon, polyvinyl chloride (PVC), polystyrene, polyethylene, polypropylene, polyacrylonitrile, silicone and many more.

Polymers are classified depending on the behaviour with the temperature in thermoplastics and thermosetting.

Thermoplastics (i.e., which in general are linear polymers) melt before degrade when they are heated, their chains are one dimensional. It allows the polymer chains to be ordered and often to crystallize. Once the polymer is formed it can be heated and rearranged over and over again. This property allows easy processing and also facilitates recycling.

On the other hand thermosetting polymers tend to have three-dimensional networks and do not melt once formed. Reheating will cause the material to degrade.

The mechanical properties of the polymer depend on the polymeric ability to create interaction between the chains. There are different forms of interaction, chemicals crosslinking and physical crosslinking [2]. Normally, the stronger interaction between chains is present, the harder the resulting polymer should be.

The chemical crosslinking in a polymer, also called primary bonds (the covalent bonds), are the intramolecular bonds that hold the polymer together. The secondary bonds or physical crosslinking that help to give the polymer its physical properties are intermolecular forces, such as hydrogen bonding for polymers that contain hydroxyl or primary or secondary amine
groups. The primary bonds will be stronger and can only be affected by chemical changes, when the secondary bonds can be affected by changing the physical conditions.

### 1.1. Physical Crosslinking

The physical attraction forces between the molecules depend on the ability to create a strong hydrogen bond between them or to be attracted just by van der Waals forces [2].

Van der Walls force is the sum of the attractive or repulsive forces between molecules or between parts of the same molecule, others than those due to covalent bonds and/or the hydrogen bonds. Van der Wall forces tend to be relatively weak compared to covalent bonds or hydrogen bonds. The more polar are the molecules, the stronger will be the attraction forces.

The hydrogen bonds are electromagnetic attractive forces between polar molecules in which usually hydrogen is linked to a highly electronegative atom, such as nitrogen, oxygen or fluorine, as shown in Figure 3. The hydrogen bond creates a higher attraction forces because they can get a disposition where the electronegative and electropositive charges of the neighbouring molecules able to be closer.

![Figure 3- Example of Strong Hydrogen Bond Interaction](image)

The higher are the attraction forces between the molecules, the more energy is necessary to break such bonds. Therefore, the higher temperature is needed.

For example as shown in Figure 4, the gases (at room temperature) of methane, chloromethane and (liquid) methanol have similar shapes and molecular masses, but the secondary forces between the molecules significantly differ and, thus, as the result these molecules have quite different boiling points. The boiling temperature of chloromethane (-24.2 °C) is higher than of the methane (-161.6 °C) because the molecule is more polar, and also, because the atom of Cl is more electronegative, thus creating a kind of hydrogen bond.
attraction. The boiling temperature of methanol (64.7 °C) is rather higher than the chloromethane, even if the molecule of methanol is less polar, because of the more effective hydrogen bond [3].

![Figure 4- Methane, Chloromethane and Methanol](image)

As shown in the previous example such intermolecular forces affect the physical property of short molecules, hence, it also should affect the resulting mechanical forces of polymolecules. The more polar the bond, the stronger the connecting forces are, thus the $T_m$ and the $T_g$ of a such polymer will be higher. In addition, the hydrogen bond creates a stronger bond between the molecules. Therefore, the polymers which contain a lot of hydrogen bonds in their chain normally exhibit very high values of $T_g$, either $T_m$. It means that they usually are not in a rubbery state at room temperature, and therefore, they tend to be rigid ones [4].

Depending of the structure of the chains the polymers can crystallize or be an amorphous polymer. The density is an important factor in the polymer. If the chains are linear and ordered they can be closer to each other and the attraction forces are higher giving as a result a tough polymer. These polymers usually form a crystallized structure when they are cooled. But when there are not ordered it become more difficult to them to be close and as a result they may not crystallize.

The fine example is the polyethylene (PE). It tends to crystallize when it is slowly cooled from molten. If it is slowly cooled from molten, the crystalline structure becomes ordered and also the molecules are long enough and thus such a resulting PE has a high density. On another hand, if such PE is rapidly cooled, the polymeric structure is not so ordered and it does not form a perfect crystallized structure, thus, it has low density. The first material high density PE (HDPE) is the toughest known thermoplastic material and it is only used when exceptional toughness is required. But the low density PE (LDPE) has much shorter molecules and thus the van der Waals forces are effectively reduced in the areas of molecular chain defects. The resulting polymer has lower tensile strength and the elastic modulus; therefore, it tends to be soft, flexible and leathery.
The bulkiness often prevents the chains from being close to each other and as a consequence the more bulkiness, the softer is the polymer.

The rigidity on the polymer chains is also another factor in the polymer behaviour. The essential differences in the polymer behaviour lay in the flexibility of the valence bonds in polymeric backbone. If such a valence bond is more flexible, thus it needs less energy to change the molecular shape by thermal oscillations. Therefore, polymers which have flexible molecules tend to be softer and have lower \( T_g \) and \( T_m \).

For example, silicones are very soft polymer group because the bond of silicon and oxygen is extremely flexible. Oxygen also has a quite flexible bond with carbon.

In the carbon-carbon bond the energetical barrier of conformational change is about 9kJ, it is still flexible at room temperature, while in a double carbon bond the rearrangement energy is twenty times higher.

In the nitrogen-carbon bond the energetical barrier is closer to the double carbon-carbon bond. Ureas do not have O-C or C-C bonds in the chain, while urethanes do. Therefore polyurea tends to be tougher than polyurethane.

\[ \text{Figure 5- Polyurea} \]

### 1.2. Copolymers

When different monomers are mixed in a chain, the resulting polymer is known as a copolymer. There it is infinite possibilities of copolymerization. Usually they are mixed to obtain better properties [5].

When the length of the blocks of each kind of monomer is long enough, the blocks start behaving as a separate polymeric material and would have some separated \( T_m \) and \( T_g \). The \( T_m \) and \( T_g \) of a block of the polymer tend to increase when it is copolymerized with another block that has higher \( T_m \) and \( T_g \).

Copolymers where each part of the chain is identical to the following, such equal blocks of polymers, are able to build strong intermolecular interactions. On the other hand those
copolymers made up by parts having different lengths and being randomly copolymerized show much lower interaction. For example, such copolymer block length variation principles are currently excessively used in soft polyurethane (PU) production.

On another hand, the copolymerization brings a significant problem, the majority of polymers are not compatible with other polymers, it means that it is impossible just to blend any copolymer and get something useful from it. Therefore, a careful consideration of the different polymeric-components is required. This process is not always cost-effective and it has to be overviewed when choosing the material.

The Flory-Huggins model is a useful approximation to the polymeric miscibility, where the change in the Gibbs fee energy upon mixing should be negative. Even though the Flory-Huggins model is a quite effective and popular tool for a basic prediction of polymeric miscibility, it is does not include such factors as the specific polymeric geometry, strong hydrogen bond formation and most important a free volume of polymer.

\[ \Delta G = \Delta H - T \Delta S \]  

In that model the change in enthalpy (\( \Delta H \)) and the change in entropy (\( \Delta S \)) can be considered separately from each other. While the first refers to a molar fusion factor and entropy refers to fain of freedom of the possible conformations of the molecules [5].

### 1.3. Polymeric Reinforcing Fillers

Additives, fillers and reinforcements are used to change and improve the properties of the polymers. Different fillers are used to lower the cost of the materials. Others additives include lubricants to reduce viscosity of the molten plastic, plasticizers to increase the flexibility of the materials, and colorants to provide colourfastness. Reinforcing polymers allows the use of polymers in increasingly demanding applications in some areas where unfilled or unreinforced polymers cannot compete. By bringing improved mechanicals properties, these polymers can compete with stiffer materials like metal [6].

If the filler is characterized with a large aspect ratio between the longest and the shortest dimensions it is called fibre. In general, reinforcing fibres increase the mechanical properties of the polymers, such as the tensile strength, the elastic modulus and the resistance to shrinkage. The fibres are usually made of boron, carbon, fibrous minerals, glass or Kevlar. Latest technical
advances are now coming from direct continuous compounding of fibres into the polymer matrix. Fibres give anisotropy to the material, fibre orientation varies with the flow direction in the thickness direction. Hence, it is important to predict these orientations, in order to predict the properties of the moulded article [7].

Plastics are normally poor electrical conductors, electrical properties can also be affected by fillers. For example, by adding aluminium powders, carbon fibre or graphite, the electrical and thermal conductivity are improved.

Extender fillers are used to reduce the material cost. Some of the fillers usually used for this are calcium carbonate, silica and clay. Calcium carbonate (CaCO\textsubscript{3}) is one of the inorganic materials most widely used as filler in polymers. It is used to modify the mechanical properties and morphology of the polymers. Calcium carbonate improves the Modulus of Elasticity, but it also decreases impact strength, toughness and elongation at break.

The next table synthesise some of the fillers depending on which properties they affect:

<table>
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<td><strong>Reinforcing fibres</strong></td>
<td>Increases tensile strength</td>
<td>Boron, carbon, fibrous mineral glass, Kevlar</td>
</tr>
<tr>
<td></td>
<td>Increase elastic modulus</td>
<td></td>
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<td></td>
<td>Increase resistance to shrinkage</td>
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</tr>
<tr>
<td><strong>Extended fillers</strong></td>
<td>Reduces material cost</td>
<td>Calcium carbonate, silica, clay</td>
</tr>
<tr>
<td><strong>Plasticizers</strong></td>
<td>Improves melt flow properties</td>
<td>Monomeric liquids, low-molecular-weight materials</td>
</tr>
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<td></td>
<td>Improves flexibility</td>
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</tr>
<tr>
<td><strong>Colorants</strong></td>
<td>Provides colourfastness</td>
<td>Metal oxides, chromates, carbon blacks</td>
</tr>
<tr>
<td></td>
<td>Protects from thermal and UV degradation</td>
<td></td>
</tr>
<tr>
<td><strong>Conductive fillers</strong></td>
<td>Improves electrical and thermal conductivity</td>
<td>Aluminium powders, carbon fibres, graphite</td>
</tr>
<tr>
<td><strong>Flame retardants</strong></td>
<td>Reduces the occurrence and spread of combustion</td>
<td>Chlorine, bromine, phosphorous, metallic salts</td>
</tr>
<tr>
<td><strong>Blowing agents</strong></td>
<td>Reduces the density of the material</td>
<td>Gas, azo-compounds</td>
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2. Polyolefin

Polyolefins are a family of polymers produced by olefins (i.e., alkenes), usually by such as \( \text{C}_n\text{H}_{2n} \). Polyolefins are currently the most important industrial group of thermoplastics. Polyolefins consist of carbon and hydrogen atoms and they are non-aromatic in main polymeric backbone. Polyolefins are usually processed by extrusion, injection moulding, blow moulding, and rotational moulding methods. Thermoforming, calendering and compression moulding are used to a lesser degree. Polyolefins usually are not receptive to inks due to its nonpolar, nonporpous and low-energy surface. Thermoplastic polyolefins usually are partially crystalline [8].

There are also some polyolefin elastomer (POE), which is used as a successful substitution of PU in the moulded flexible foam technology such as in the fabrication of self skinned footwear (for example, Crocs shoes), seat cushions, arm rests, spa pillows, etc.

Besides its low density, they are also distinguished by excellent chemical stability, low water absorption and good electrical insulation properties. Polyolefin surface have excellent chemical inertness, they are unaffected by common solvents. Thus, they are not usually joined together by solvent welding. But the chemical inertness decrease at lower and higher temperatures. Therefore, thermal welding is commonly used as a bonding technique [9].

The most popular polyolefins are polyethylene (PE) and polypropylene (PP). They are excessively used due to their low cost and wide range of possible applications.

Polyolefins have generally quite advance properties, such as low density, low water absorption, excellent chemical stability, high resistance to corrosion and excellent electrical insulator. On the other hand, some disadvantages of polyolefins are high thermal expansion, flammability, difficulty to bond and low UV/weathering resistance of some of polyolefins.

2.1. Polyolefin Elastomers (POEs)

Polyolefin elastomers are a relatively new class of polymers that emerged with recent advances in polymerization catalysts. POEs can be substituted for number of generic polymers such as ethylene propylene rubbers, ethylene vinyl acetate, poly vinyl chloride, etc. They are compatible with most olefinic materials and they are used to modify plastics [8]. They are
primarily used in thermoplastic olefins via impact modification of polypropylene. Most commercially available POEs are copolymers of either ethylene-butene or ethylene-octen.

Polyolefin elastomers are copolymers of ethylene and another alpha-olefin, such as butane or octane. POE is produced using metallocen catalyst, which selects the ethylene and comonomers sequences. It produces polymers with higher elasticity because the copolymer disrupts the polyethylene crystallinity. Furthermore, if the molecular weight of the comonomers is higher it provides enhanced polymer toughness.

### 2.2. Silane-Crosslinked Polyolefins

Monomeric silicon chemicals are known as silanes (SiH₄) and a silane that contains at least one silicon-carbon bond is known as organic-silane (e.g., Si-CH₃). The silicon-carbon bond is very stable and non polar.

Organofunctional silanes are molecules that contain two different reactive groups on their silicon atom, hence they can react with different materials. They have an important value as coupling agent.

One way to improve performance of plastics is to crosslink them to some degree. One example is the crosslinking of polyethylene to give partially crosslinked polyethylene or PEX using Organofunctional silanes. This is achieved by the new crosslinked SIOPLAS technology, patented by Dow Corning. It consists in two-step process based on the chemistry of organofunctional silanes. Firstly, the organofunctional silanes are grafted on polyolefins chains and secondly the siloxane crosslinkages (Si-O-Si) are formed. The vinyl groups allow for grafting on the PE backbone, and the alkoxy groups allow for subsequent crosslinking between the PE chains upon exposure to heat and moisture [10].

The silane grafting reaction is very fast and it allows the choice of reactivity suitable to an exact the industrial processing method. Within a few minutes of the residence time of all components in the extruder, very high grafting yields are obtained (at least 80% of the added silane is grafted on the PE) in an optimized industrial process. The reactive processing techniques enable silane grafting onto any kind of olefin (LDPE, HDPE, PP, etc.). It is mainly used in pipes, wire and cable insulation.
Silanes have other applications like the treatment of fillers to increase reinforcement as additives in inks, coating and sealants to improve adhesions.

2.3. Polyethylene

Polyethylene (PE) is the simplest polymer of the polyolefin group. It repeats the ethylene monomer \( \text{C}_2\text{H}_4 \). It consists from linear chains of the carbon atom in the backbone and a couple of hydrogens attached to each carbon. Its structure normally is quite linear. Therefore, it allows the chains to be close to each other, and hence, despite the weak van der Waals attraction the resulting attraction force between PE molecules is reasonably high and thus able to give a very dense structure [11].

Polyethylene is classified into several categories based mostly on its density and branching. Its mechanical properties depend on the extend and type of branching, the crystalline structure and the molecular weight.

As explained before, the high density polyethylene is only used when extremely high properties are required, such as bulletproof vest because, as it is very expensive to synthesize.

On the other hand, the low density polyethylene is the most common plastic. It is primary use in packaging (i.e., plastic bag, film, containers including bottles).

Ethylene is a quite stable molecule and it only polymerizes upon contact with catalysts. The conversion is highly exothermic. The most common catalyst consists of titanium chloride, and it is called Ziegler-Natta catalysts.

2.3.1. Polyethylene-Propylene Copolymer

Polyethylene often is copolymerized with polypropylene. Propylene is also a polyolefin and it repeats the propylene \( \text{C}_3\text{H}_6 \) monomer. The copolymer polyethylene-propylene is a rubber created from the blend of two reasonably rigid crystalline polymers. The monomers of ethylene and propylene groups do not have enough chain length to achieve high values of intermolecular interaction; as a result, it is soft and flexible [8].
The molecule of ethylene and propylene is combined to form a tough and flexible material which is used as an engineering plastic which can compete with other materials like ABS. The copolymer is more resistant to the impacts than PP pure and more flexible than PE.

2.3.2. Conclusion on the PE

Polyethylene has a wide range of use as grocery bags, shampoo bottles, children’s toys and even bullet proof vests. This material can be very tough and have very useful properties, such as it is not toxic, flexible, waterproof, economic and transparent. It is also resistant to low temperatures. Its surface is inert and it makes difficult to paint it. It can be melted and reused.

Polyethylene is the simplest and the most popularly used polymer in the world. It is due to its low cost and to the facilities on the processing. If the polymeric chains are long enough and the polyethylene polymolecules tend to be more linear, the tensile strength and the elastic modulus will be high, but the cost of such polyethylene will also increase.

The copolymerization with propylene gives a very competitive engineering plastic, but it makes more difficult to recycle it.

2.3.3. Ethylene Vinyl Acetate (EVA)

Ethylene vinyl acetate (EVA) is a copolymer of ethylene and vinyl acetate. It is a polyolefin and the weight percentage of ethylene varies from 90 to 60%. This material has similar softness and flexibility of elastomeric material, but it can also be processed like other thermoplastics. EVA can be injected like other polyolefins (LDPE, HDPE, etc.). This material has good clarity and gloss and low temperature toughness. It is resistant to UV radiation [8].

![Figure 6- Ethylene vinyl acetate (EVA)]
EVA is an extremely elastic material that can be sintered to form a porous material similar to rubber. It is three times as flexible as LDPE. EVA is one of the materials popularly known as expanded rubber or foam rubber. EVA foam is used in equipment for sports such as ski boots, bicycle saddles, hockey pads, etc. It is typically use as a shock absorber in sport shoes. EVA sleepers and sandals are very popular because its good properties like light weight, easy to mould and glossy finish. Besides, it is cheaper compared to natural rubber and EVA can be used as a substitute for cork in many applications. Hot melt adhesives are usually made from EVA, they usually contain additives like wax and resin.
3. Polyurethane

Polyurethane (PU) is a large family of polymers. A polyurethane is polymerized by the reaction of a isocyanate (where 2 or more organic isocyanate groups (OCN-R-NCO) attached to the pre-polymer) and a polyl with 2 or more hydroxyl group (HO-R-OH) with the same proportion (i.e., stoichiometry) close to NCO : OH is 1:1, where number of NCO is normally slightly higher than OH number. The molecules begin to bind on both sides, therefore PU pre-polymer molecules can grow into a high molecular weight polymolecule.

Isocyanates are very reactive materials, specially the aromatics ones. While the aromatics start to react from 80 °C (in absent of additional catalyst), the aliphatic ones normally require elevated temperatures of 160-180 °C. Normally, a catalyst is used to increase the reactivity of an isocyanate.

Polyols are pre-polymers, and they are polymers in their own right which have on average two or more hydroxyl groups (-OH) per molecule. Depending on which diisocyanate and polyl are used the final properties of the polymer change: crystallinity, mechanical properties, biodegradation, etc. Particularly, it is the length of the polyl used and also its functionality, that contributes much to the final properties.

The polyols used for production of a rigid polyurethane have molecular weight in hundreds and for flexible the molecular weight is up to ten thousand or more.

Polyurethanes can be thermosetting or thermoplastics depending to the behaviour with the temperature. Most of them are thermosetting.

Primary and secondary amine as a substituted urea can also react with isocyanate to obtain so called polyuria-polyurethane. This reaction with primary amine is very fast, when with secondary amine it requires higher temperature than the reaction between isocyanate and hydroxyl [12].
The isocyanate reacts with water giving a secondary amine and CO$_2$, then the amine reacts with an isocyanate at it gives the substituted urea, as shown in Figure 7.

The reaction between isocyanate and a substituted urea gives a crosslinked polymer as a result. Crosslinking gives to the polymer three-dimension, and it means that the molecular weight is high. As a consequence, when the polymolecules are heated they do not soften or melt (i.e., thermosetting polymers).

The rigidity of the polymer also depends on the architecture of the isocyanate. Aromatic isocyanates give more rigid polymer than aliphatic because of the bulkiness and the polarity of the ring. Usually the most rigid polymers are based on the isocyanate phenyl 1,4-diisocyanate. The polyurethanes which are based in 4,4- MDI are more flexible, because even if they have two rings, the angle of 60° in the connecting methylene group decrease polymeric density and thus gives more flexibility to the polymer.

Polyurethanes which are based on TDI do not have straight polymeric chains, therefore the degree of crystallinity is lower. It is a popular choice in production of soft foams and elastomers.

HDI is an aliphatic isocyanate, the resulted polyurethane can have a high tensile strength, because its chains are very straight and they can be ordered giving a crystalline polymer, even higher than a similar polymer based on aromatic MDI.
3.1. PU Foams

Foam forming PU are normally thermosetting polyurethane, during the polymerization process of foam the water is presented into the reaction, and depending on the quantity of water more or less CO$_2$ is formed. In some application an additional low boiling temperature blowing agent may be used. The polyurethane foams are often used to isolate buildings, it consists in a spray that contains two parts (isocyanates and polyols) and they are mixed at the site of installation.

3.2. Thermoplastics Polyurethanes (TPU)

Thermoplastics polyurethanes consist in block structure polyurethane. In some cases the chains are made by segments of molecules with different kinds of used polyl. Some of them are flexible segments and other may be rigid segments. There are unlimited combinations of the blocks. These blocks are boned by covalent links.

The hard segments usually are formed by the reaction of the diisocyanate with short-chain diols. They are also called chain-extenders and contain high polarity while soft segments are formed by the reaction of the diisocyanate with long chains and they contain low polarity.
The high polarity in the hard segments creates a strong attraction between them and it gives an aggregated structure to the polymer. The polymer forms crystalline or pseudo crystalline areas located in a flexible and soft matrix. The crystalline area acts as a physical crosslink and the soft matrix gives the elasticity to the polymer.

These pseudo crosslinks (i.e., physical crosslinks) disappear with the heating, it means that it is possible some processes like classical extrusion, injection moulding and calendering processing methods and TPU scrap can be reprocessed. TPU that can be found on the marked classified into groups depending on the soft segment chemistry.

3.3. Conclusion on Polyurethane

Non-porous or high density (500-1200 kg/m³) rigid polyurethanes are used to make auto parts, shoe soles, yacht parts, parts of furniture and decorated skateboards or by injection techniques, casting or even RIM (Reaction Injection Moulding).

This material has an excellent abrasion resistance and combine excellent mechanical properties with rubber-like elasticity. It has also high transparency. It can also be copolymerized with other products, giving a more flexible material, to produce textile fibres, such as spandex or lycra industry. Polyurethane can also be recycled like others thermoplastics, such as polyethylene, polypropylene, etc.

On the other hand polyurethanes have some disadvantages. It tends to absorb water, and the durability of aromatic polyurethanes decrease when exposed to sunlight or organic solvents. It also often emits some odours. Although, they are not very noticeable, a prolonged exposure to it can provoke injuries to people.
4. Blend of Polyurethane and Polyolefin

Blending of polymers is an economically attractive approach to develop new materials with desirable properties of more than one polymer. Also the incorporation of particulate fillers into polymeric matrix, as explained in paragraph 3.1., is an extended technique to improve or modify some properties and also to improve their processing capability and to reduce product cost. Nowadays, requirements for the production of new polymers with the best cost/performance balance are increasing. Therefore, research based on the study of polymer blends and polymer filler composites is extensive.

Thermoplastic polyurethane (TPU) is a versatile material but has a high cost. Melt blending of TPU with polyolefin (PO) can lower the cost of the material and also improve mechanical and chemical properties. TPU and PO are highly incompatible because they have different polarities and high interfacial tension. Most of immiscible blends are thermodynamically unstable, but it is possible to stabilize it and this process is commonly called compatibilization. Compatibilizers serve as polymeric surfactants for immiscible blends by migration to the interface and lowering the interfacial tension. Polypropylene copolymer is a good compatibilizer between TPU and PO.

A study performed on the morphological, mechanical and thermal properties of blends of TPU and PO Institute of Science & Technology for Advanced Studies & Research [13] gave as a result that the blend of PU and PO after incorporating PPCP as compatibilizer and calcium carbonate as filler gives excellent performance in all aspects.
5. Toxicity of Polymers

Plastics are very important in our society and offer numerous benefits for human health and the environment. Plastic is the current most important material for packaging, they protect food and goods from getting wasted or contaminated also clothes and safety equipment like fire proof materials, helmets, etc, which protect people from hazards. Polymers are also important for medical applications (tubings, prosthesis, etc).

But, on the other hand, several hazardous substances may be released during the life cycle of a plastic. The plastic polymers are not considered as toxic, but several of the chemicals used to produce plastics are hazardous for human health and the environment. In a plastic polymer can be some non-bound residual monomers and additives which have toxic properties. Also the degradation and combustion of polymers results in toxic chemicals [14].

Because the most hazardous components are in the production of the polymers, therefore it is very important to control the exposition of the workers in the plastic industry. The main route of exposure is the inhalation and absorption through the lungs because a lot of component is volatile. These volatiles compound are mainly emitted during the production, but also during the use of them.

Consumers are also exposed to some very volatile compounds which are found in plastics. Infants and elders are particularly sensitive to hazardous chemicals.

For example baby bottles made polycarbonate have been retired because of the risk of bisphenol-A filtering through the bottle.

5.1. Toxicity of Polyolefins

PE is considered safe and it is used in a rage of environments, but the toxicity and flammability of the polyethylene depend on the plasticizers that are added to the polymer and the compounds that are used to bond it.

High density polyethylene (HDPE) is considered safe to use in normal conditions, however this plastic may leach when exposed to UV, heat and over time from natural breakdown. Bottles that are made of this material should not contain hot liquids, remain out in the sun or being
reused. Low-density polyethylene is rarely used in products that would affect human health. This plastic is considered safe but not very environmentally - eco-friendly [15].

Polyethylene-terephthalate is widely used in production of plastic bottles because it is an excellent water and moisture barrier material. It is associated with hormonal imbalances, allergies and reduces the fertility. Some studies show that it may also contribute to the development of obesity and breast cancer.

5.2. Toxicity of Polyurethane

The toxicity of polyurethanes is generally due to the unreacted isocyanates. Some of isocyanates are solid at room temperatures but others are very dangerous because are readily vaporised liquids.

Isocyanate are very reactive, they readily react with water giving ureas. Also, the deposit of isocyanates must be well close to prevent water from entering, because if some water enters the reaction can break the deposit of isocyanate.

Isocyanates react violently with base, secondary or primary amines and alcohol. In the production of polyurethane the isocyanates deposits should not be near to the other components.

TDI is still one of the most important commercially used isocyanate, despite the fact that it is very volatile. Humans may be exposed to TDI by inhalation, ingestion, dermal and eye contact during the production of polyurethane. TDI is a powerful irritant to the mucosal membranes of gastrointestinal and respiratory system, eyes and skin. It can cause asthma and intestinal obstruction. Therefore, TDI is due to be banned for use in EU [16].

Isocyanate may contain dangerous components and it can affect skin and respiratory system. Also amines, glycols and phosphate present in spray polyurethane foams present risks.

Polyethylene glycol is used as a suitable soft segment for a polyurethane backbone in order to give at room temperature a soft and rubbery product. This component can cause allergic reactions in certain individuals. Some people experience nausea, flatulence and diarrhea after being exposed to it, while others get a hives-like rash. The elderly seems to be particularly prone to these side effects.
5.3. Environmental Impact of Plastics

Environmental problems that may arise in polymer manufacturing projects include emissions to air, wastewater, hazardous chemicals and noise.

The most common emissions to the atmosphere in the polymer production are volatile organic compounds (VOC) from polymeric solvents drying, finishing and purging and there are some recommended actions in order to reduce the emissions. Wastewater from industrial processes may contain traces of hydrocarbons, polymers, surfactants, emulsifiers, oxygenates, acids, inorganic salts and heavy metals.

Polyethylene does not biodegrade easily, it can remain in a landfill for hundreds of years. PE scrap can be melted and reused. The combustion of polyethylene can produce many useful products, the nature of which depend on the external conditions such as temperature and oxygen availability. The final products formed during the complete combustion are carbon dioxide (CO$_2$) and water (H$_2$O). Under incomplete flaming other low-weight hydrocarbons and oxygenated compounds such as CO, alcohols, etc are also generated. In an inert atmosphere polyethylene combustion does not produce CO or CO$_2$ [14].

Polyurethane polymer is a combustible solid and can be ignited if exposed to an open flame. Decomposition from fire produces CO and trace nitrogen oxides and hydrogen cyanide.
7. Health & Safety

During the production of the shoe soles the workers may be exposed to toxic products and it will be important to ensure that they will have the suitable protection in order to avoid them from poison and/or injuries, and also that the workplace environment is adapted to their capabilities.

Occupational Health & Safety (OHS) is an area concerning the safety of people engaged in work or employment. OHS also protect co-workers, family members, employers, costumers and many others who may be affected by the workplace environment.

OHS is important for moral, legal and financial reasons. Moral obligations ensure the protection of employee’s life and health. Legality involves preventive and punitive and compensatory effects of law that protects safety of workers. OHS can reduce the cost of injury and illness, including medical care and disability benefit costs.

OHC has three important objectives:

- The maintenance of working health and working capacity
- The improvement of working environment
- Development of work organisations which and working cultures which supports health & safety

Physical hazards are common in many industries. There, it is important to have safety methods and procedures to manage risks.

In the production of polymers workers could be exposed to toxics chemicals [17]. It is important to have the right personal protective equipment. Confined spaces that have bad ventilation could be dangerous to the workers and to people who try to rescue them. Machines also are a risk for workers: moving parts, sharp edges, hot surfaces. In order to minimize the risk some lockout- tagout procedures should be used. Noise is also a work-place hazard, as hearing loss is one of the most common injuries in industry.
7.1. European Agency for Safety and Health

The European Agency for Safety and Health (EU-OSHA) at work is in charge to making Europe a safer, healthier and more productive place to work. OSHA promotes a culture of risk prevention to improve working conditions in Europe.

It has different tasks, such as inform the companies on the importance on workers’ health and safety for European social and economic stability and growth. OSHA shares knowledge and good practices on safety and health and design instruments to evaluate the workplace risks.

EU-OSHA works side-by-side with governments, employers’ and workers’ organisations, EU bodies and networks, and private companies.

7.2. The European Chemical Agency

The European Chemical Agency (ECHA) manages the technical, scientific and administrative aspects of the Registration, Evaluation, Authorization and Restriction of Chemicals system [18]. It is the main European regulatory authority in implementing the chemicals legislation for the benefit of human health and the environment as well as for innovation and competitiveness. ECHA works with companies to provide them information about chemicals and the safe use of them. ECHA also works the European Agency for Safety and Health at Work (EU-OSHA).

By law, workers must be aware about how hazardous are the chemicals that they handle and how can they use them safely. Suppliers of hazardous substances need to include information in the safety data sheets and on labels and the employers have to use this information to put risk management measures. These legal requirements apply equally to all companies in all EU countries.

In the case of polyurethanes preventing exposure to isocyanates is a critical step in eliminating the health hazard. There are some methods for minimizing isocyanate exposure such as closed systems and good ventilation. Also personal protecting clothing and equipment may be necessary. Early recognition of sensitization and strict elimination of exposures is essential to reduce the risk of respiratory problems for workers who have become sensitized [17].
8. Quality Endorsement Standards (EN ISO 9000 and EN ISO 90001)

The EN ISO 9000 is a family of standards related to quality management systems. It is designed to help the organisations to achieve the needs of the customers and other stakeholders while meeting regulatory requirements related to the product. The standards provide guidance and tools for companies and organisations who want to ensure that they meet customers’ requirements and that the quality is consistently improved. There are number of standards in the ISO 9000 family, including:

- ISO 9001:2008 - sets out the requirements of a quality management system
- ISO 9004:2009 - focuses on how to make a quality management system more efficient and effective
- ISO 19011:2011 - sets out guidance on internal and external audits of quality management systems

8.1. The eight quality management principles

ISO 9000 standards are based in eight quality management principles. These principles can be used by senior management as a framework to guide their enterprises towards improved performance. These principles are included in ISO 9000 and they are derived from the collective experience of experts who participate in the ISO Technical Committee. They are also responsible for developing and maintaining the ISO 9000 standards [19].

Principle 1: Customer focus

Commercial organisations depend on their customer/customers, therefore they should understand customer needs, meet customer requirements and strive to exceed customer expectations. This principle leads to measuring customer satisfaction, ensuring a balanced approach between satisfying customers and other stakeholders (such as owners, employees, suppliers and society as a whole). As a result the customer loyalty will be improved.

Principle 2: Leadership

Leaders must establish a clear unity of purpose and direction of the organisation. People will understand and be motivated towards the organization’s goals and objectives. It is important to set challenging goals and targets while considering the needs of all interested parties including customer, owners, employees, etc. Leaders must inspire, encourage and recognize people’s contribution.
Principle 3- Involvement of people
People are the essence of an organisation or enterprise, their involvement is essential to use their abilities for the organization’s benefit. People must feel free to share their knowledge and experience. People participation contributes to continual improvement.

Principle 4- Process approach
When activities and related resources are managed as a process the results are achieved more efficiently and the costs and the cycle times decrease because of the effective use of the resources. Process approach leads to focusing on resources, methods and materials, analysing and measuring key activities, evaluating risks and consequences of activities on customers, suppliers and other stakeholders.

Principle 5- System approach to management
In order to achieve the goals of the organisation effectively it is important to identify, to understand and to manage interrelated processes as a system. It is necessary to structure the system and to provide a better understanding of the roles and responsibilities in order to reduce cross-functional barriers.

Principle 6- Continual improvement
The key of the success is to be continuously improving the organisation performance. Providing people with training in the methods and tools of continual improvement and making continual improvement of products is important to react quickly to the opportunities of the market.

Principle 7- Factual approach to decision making
Decisions have to be based on the analysis of data and information using valid methods. Data and information must be sufficiently accurate and reliable and must be accessible to those who need it.

Principle 8- Mutually beneficial supplier relationships
A beneficial relationship between an organization and its suppliers enhances the ability of both to create value. In order to achieve a good relationship, it is important to have clear and open communication, sharing information and future planes and establishing together development and improvement activities.
8.2. ISO 9001

ISO 9001 contains the requirements that organisations must meet to get the standard. Not all organisations are certified by this standard. ISO, the international Organisation for Standardization, publishes the standards, and independent certification bodies provide information that organisations have the requirements of 9001. It is the only standard in the family that can be certified. It can be used by any organisation, large or small and in any field of activity.
9. Injection Moulding

Injection moulding is a manufacturing process for forming some parts that often have complicated shapes. Both polyethylene and polyurethane are used in injection moulding. The materials that are usually used for this process are mainly thermoplastics and thermosetting polymers, but also metals, glasses, elastomers, etc.

This process consists from an injecting the material into a mould which gives it the desired shape. The material is heated in order to flow better during the process and to enter easily in the mould. The heated material is forced to enter into the mould cavity with a ram or screw. Inside the mould the material cools and became hard to keep the final configuration and solidify. Polymers keep their shape when they are cooled below their $T_g$ [20, 21].

Thermoplastic polymers are the mostly used material for this process, due to their good characteristics such as the ease to be recycled, that they flow easily when they are heated because the bond between the chains break.

Thermoplastics more often used than thermosetting, as they are safer than thermosetting for this process, because if thermosetting injection is not done in a timely manner, chemical crosslinking could appear and it would stop the screw and damage the injection moulding machine.

The injection is done with high pressure, moulds can be of a single cavity or multiple cavities. Moulds are generally made of tools steal, but sometimes also of aluminium or stainless steel applied. Aluminium is not used for high volume production or for parts with narrow dimensional tolerances because they have worse mechanical properties, and thus it gets damaged rapidly. But if the volume of production is not particularly high, such aluminous moulds are reasonable, because such mould fabrication cost and the time are significantly reduced. Most steal moulds are fabricated in order to do over a million parts and can cost hundreds of thousands of Euros [22].

For thermoplastics, typically the granulated raw material is fed through a hopper into a barrel where is heated. The van der Waals forces make the bonds between the chains, but when the thermal energy increases the space between the molecules, and in consequence these forces weaken and the polymer flow easily. This reduces its viscosity.
The screw moves the material forward, mixes and homogenizes it. The material is collected in the front of the screw into a volume known as a shot. Shot is the volume of material which is injected in one mould considering the contraction and a quantity of material which remains in the barrel in order to avoid that the screw arrives until the bottom.

Then the material is forced into the cavity at high pressure, the pressure is applied until the material in the gate of the cavity solidifies. The full injection cycle time is often under than one second. The pressure applied to thermoplastics is quite high compared with other materials.

Finally the screw goes back and takes material for the next cycle, while the material in the mould solidifies. The time of cooling is reduced by applying cool water or oil. Ones the cool temperature of the material is achieved the mould is open and the part is demoulded.

For thermosetting polymers usually two different chemical components are injected in the barrel, that components made chemical reactions which crosslink the material into a network of molecules. If the molecules crosslink in the barrel or the screw it will damage the machine, therefore in order to avoid such an effect the time that the components are in the barrel has to be very limited. The residence time can be reduced by minimizing the volume of the barrel. In order to achieve a solidified thermosetting component in less time, the mould is hot and thermally isolated. It means than the chemical reactions occur faster.

![Injection Molding Machine](image)

**Figure 9- Injection Moulding Machine**

Common polymers that are used in this process are epoxy and phenolic (thermosetting) and nylon, polyethylene and polystyrene (thermoplastic).
9.1. Intensification ratio

In the injection moulding machines, the hydraulic power is converted into plastic pressure (melt pressure in the nozzle). The hydraulic piston pushes the screw and the non-return valve pushes the plastic though the nozzle into the mould. The hydraulic piston has a larger surface than the valve (for example 100 cm² and 10 cm² respectively). This large to small ratio of ram areas causes the hydraulic pressure to be intensified or multiplied by a factor of 10 because of the law of physics F=P x A. The machines intensification ratio ranges from 6:1 to 43:1. It is the plastic pressure that pushes the plastic into the mould [23].

Ideally, in order to calculate this ratio, the ratio of the screw diameter and the functional hydraulic ram diameter will be used to calculate the areas. Nevertheless, it is not easy to find it in the machine manuals. Another way is to identify in the machine specifications the maximum plastic or melt pressure that the machine can develop and check in the machine controller the maximum hydraulic pressure allowed to set.

\[ Ri = \frac{\text{Maximum injection (plastic) pressure}}{\text{maximum hydraulic pressure for the injection unit}} \]

Once the ratio is found, in order to calculate the plastic pressure for backpressure, we only need to multiply the hydraulic pressure times the intensification ratio.

\[ \text{Area of Non-Return Valve is } 645.16 \text{ mm}^2 \]
\[ \text{Area of Ram is } 6451.6 \text{ mm}^2 \]

\[ \text{Intensification Ratio is } 10:1 \]

Figure 10- Intensification Ratio Diagram
9.2. Viscosity

The viscosity of a fluid is a measure of its resistance to gradual deformation by shear stress or tensile stress. The shear stress of a Newtonian fluid is linear proportional to the velocity gradient, and its behaviour can be described with the next equation, where the viscosity is the constant of proportionality:

\[ \tau = -\mu \frac{\partial v}{\partial y} = \mu \dot{\gamma} \quad (2) \]

where:

- \( \tau \) the shear stress exerted by the fluid
- \( \mu \) the fluid viscosity – a constant of proportionality
- \( \frac{\partial v}{\partial y} \) the velocity gradient perpendicular to the direction of shear

The fluids that do not follow the equation (2) are known as non-Newtonian. Within the non-Newtonian fluids, the relation between the shear stress and the shear rate is not linear as in the Newtonian fluids, and they can even be time-dependent. Non-Newtonian fluids can be classified in two categories: time-independent and viscoelastic [5].

8.2.1 Power-Low

Also known as the Ostwald-de Waele power law, this mathematic model describes approximately the behaviour of a real time-independent non-Newtonian fluid. It is commonly used in practical applications because its simplicity [24].

\[ \tau = K \left( -\frac{\partial v}{\partial y} \right)^n = \left[ K \left( \frac{\partial v}{\partial y} \right)^{n-1} \right] \left( -\frac{\partial v}{\partial y} \right) = \mu_{\text{app}} \left( -\frac{\partial v}{\partial y} \right) \quad (3) \]

Where:

- \( K \) the flow consistency index (SI: Pa.s^n)
- \( \frac{\partial v}{\partial y} \) the shear rate or velocity gradient perpendicular to the plane of shear
- \( n \) the flow behaviour index
- \( \mu_{\text{app}} \) is the apparent or effective viscosity and it depends on the shear rate
The flow behaviour index will predict the behaviour of the fluid. When \( n<1 \) the fluid is called shear-thinning or pseudo plastic and it flows easier with increasing shear rate. Contrarily, when \( n>1 \), the fluid is called shear-thickening or dilatant and the resistance to flow increases while increases shear rate. When \( n=1 \), it is a Newtonian fluid because the apparent viscosity is constant. This model can be only be used across a limited range of shear rate, because the values of apparent viscosity tends to \( \mu_0 \) and \( \mu_\infty \) as shown in figure 11.

![Figure 11 - Power-law Model of Pseudo plastic Material](image)

8.2.2. Importance of the Viscosity in Injection Moulding

The viscosity has a high importance to Injection Moulding because the material is subjected to large amount of shear forces during the cavity filling stage.

All plastics are non-Newtonian, it means that their viscosity does not remain constant over a given range of shear rates. At lower shear rates, the plastic is non-Newtonian but as the shear rate increases, the plastic tends to exhibit a Newtonian behaviour. This happens because with increasing shear rate, the polymer molecules start to untangle from each other and start to align themselves in the direction of flow. The graphic bellow can be split in two regions, the Newtonian and the non-Newtonian. If the shear rates are in the non-Newtonian region of the curve, then small variation in the shear rates will cause a large variation in the viscosity. This
will make the mould filling inconsistent. It is therefore important to find the Newtonian region of the curve and set the injection speed (shear rate) in this region. The effect of shear rate on viscosity (speed) is greater than that of the temperature. Hence, as long as the actual melt temperature is within the recommended range, the viscosity curve will be similar [21].

Figure 12 - Curve of Viscosity of Plastics

During a flow of melts of polymolecular materials, shear thinning is generally observed, such as the example observed in the Figure 11 and 12. Shear thickening is a rear phenomena and often just observed in cases of flow of melts polymers which tend to stress-induced crystallisation or in melts of some telechelic polymers. In this case crystallation is induced directly by the elongation on a sample. Polyethylene and polypropylene tend to stress-induced crystallisation, while polyurethane is telechelic, hence those polymers may show shear thickening.

8.3.3. Telechelic Associated Polymers

In some cases polymeric melts which exhibit strong hydrogen bond formation tend to form an associated gel-network or diluted crosslinking systems during flow. These are telechelic associated polymers which are able to increase their viscosity during a deformational flow. But if the speed of flow exceeds certain values, then the viscosity only decreases. Hence, during very fast flow all known polymeric materials tend only to shear thinning [26].
9.3. Filling Pressure

Within the injection moulding process, the plastic flows through the different sections of the machine and the moulds thanks to the pressure applied by the injection moulding machine. Due to drag and frictional effects there is a loss of the applied pressure at the flow front of the plastic. Furthermore, when the plastic hits the walls of the mould, it begins to cold and the viscosity of the plastic increase. Hence, additional pressure is required to push the plastic. The skin of plastic formed at the walls reduces the area that the plastic flows through, the decrease of this area results in pressure drop. The moulding injection machines have a limited maximum amount of pressure available to push the screw at the set injection speed. The required pressure to inject the plastic at the set injection speed should never be more than the maximum available pressure. It is important the maximum pressure available is never reached. Furthermore, the maximum injection pressure should not be more than 80% of maximum available pressure on the moulding machine. It is also important to avoid sudden increases in pressures between sections, the transitions should be as smooth as possible. Conducting a pressure drop study is one of the important steps during the mould qualification process [26].

9.4. Thermoplastic Mould Maintenance

In moulding processing some problems can appear, such as, for example the piece is not entirely demoulded and some rest of materials stay in the mould. In order to avoid these problems there are some products that can protect the investment and to improve the thermoplastic operations. Some of these products are cleaners, lubricants and protective agents.

Cleaners are designed to remove deposits of thermoplastics resins, colours and additives from mould. Some cleaners are design to solve polymers with the exception PP and PE.

Lubricants eliminate and prevent the breakage and seizing of ejector pins. The lubricant film displaces moisture and provides excellent lubrication and protection against corrosion.

Protective agents are used to protect metal surfaces against the attack of water, oxygen and other corrosive agents. Corrosion damages metal surface, weakens and finally destroys their properties. Anticorrosion agents are based on oils combined with highly active corrosion inhibitors.
9.4.1. Mould Release Agents

Within thermoplastic processing operations there are some important factors that define the quality of the process: optimization of cycle time, consistency of surface finish, reduction of post mould operations prior to painting, gluing or welding [27].

The release agents help to improve these factors, they are coated onto some plastic films in order to prevent polymers from bonding to the moulding surface. Release agents, also known as demoulding agent, aid in the separation of a mould from the material being moulded and reduce the imperfections in the moulded surface.

There are different kinds of release agents depending on the material, the most common are those made of silicone and wax. Nevertheless, solvent based products and water-based products are largely used in plastic production as mould release agents. Water-based release agent is a result of more focus on health, environment and safety issues. This has resulted in development of new technologies in this area which have focused largely on water-based formulations and the movement has been away from petroleum or solvent-based products.

Polymers such as polyurethane, a type of polymer joined together by urethane links, is one such type of material that can perform well with water-based agents. The price of water-based release agents is always the same, while chemical-based mould release agents’ price fluctuates with the oil market. When oil prices are low, the cost can be the comparable to producing water-based mould release agents. Chemicals can be responsible for odours and certain reagents that can cause discomfort for those using the finished product. Water-based agents typically do not encounter these problems, but they have often been perceived as unreliable due to their tendency to improperly absorb chemical ingredients. This deficiency can be improved by increasing the addition of emulsifying agents.

The mould release agent is usually sprayed into the mould. Mould must be cleaned with solvent before spraying in order to be sure that the mould does not have rust or other pollutants. The following table compares some releasing agents.
<table>
<thead>
<tr>
<th>Mould detaching</th>
<th>Water-based and Solvent-basted type releasing agents</th>
<th>Silicone-type releasing agents</th>
<th>Wax-based releasing agents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film layer characteristics</td>
<td>Dty film layer Thin film layer (0.1～1.0μm) Low surface tension Oil-repellent and stain-proofing properties</td>
<td>Oily film layer Thin film layer (1～20μm) No oil-repellent or stain-proofing properties</td>
<td>Solid film layer Thin film layer (30～50μm) No oil-repellent or stain-proofing properties</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mould releasing mechanism</th>
<th>Interface plus layer separation</th>
<th>Layer separation</th>
<th>Layer separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristics</td>
<td>Excellent mould releasing capability and a cleaner mould surface results in a lower defect ratio.</td>
<td>Excellent mould releasing capability and workability. Often penetrates into moulded articles so that secondary processing of moulded articles is difficult.</td>
<td>Excellent ease of application. Mould surface easily becomes contaminated.</td>
</tr>
</tbody>
</table>

*Table 2- Release Agents*
10. Soles of shoes

The sole is the bottom part of the shoe. It is the part that comes in direct contact with the ground and it is also called the “outsole” of the shoe. They can be made of a variety of materials. Depending on the materials they provide different properties, some materials can provide more traction, while others provide more flexibility. Therefore, it is important to choose the correct material depending on the activity which is practiced with the shoes. For example, a ballroom dancer might prefer a shoe with a smooth leather outsole in order to turn and glide in, while a hiker needs a sole that is thick, durable and waterproof [28].

![Figure 13- A Worker Demoulds a Polyurethane Sole](image)

10.1. Polyurethane Soles

Soles of Polyurethane (PU) are found in a wide range of footwear types. They are best known for sports and trekking shoes and boots, but they are also often used for business and fashion shoe soles. The durability of polyurethane sole is quite high. People usually stop wearing a pair of shoes because they have gone of fashion, but when they are eventually thrown out, the polyurethane soles can be used together with other solid waste as an energy source.

![Figure 14- Durability of Shoe Sole Materials](image)
10.1.1. Thermoplastic Polyurethane (TPU)

Thermoplastic PU shoes’ soles are processed by injection moulding. The TPU soles are highly resistant to abrasion, they have longer life than natural rubber soles and better resilience property. This makes walking more comfortable, besides they show a good gloss and mate aspect when the product is finished.

The chemical composition of polyol and isocyanate in predetermined quantities, provide a flexible, resistant to abrasion, grease, oils and hydrocarbons, suitable for the preparation of Safety Footwear features non-slip. The soles of polyurethane have significant reduction in weight compared to other soles.

10.1.2. Polyurethane Foam Soles

They are processed by applying spray polyurethane into a mould. One way of achieving different densities of polyurethane can be achieved by varying the amount of air bubbles in the compound. Alternatively, the reaction of PU-based isocyanate with water gives CO₂ bubbles and anime which further reacts in order to produce polyuria-urethanes. Polyurethane foams, produced by both named methods, with more bubbles will show more shock absorption while will decrease its durability.

Dual density polyurethane is used to improve sole’s properties. It consists in combining two different densities of polyurethane (tough on the outside and soft on the inside) to increase the durability and shock absorption of the sole. The bottom part of the sole contains fewer bubbles in order to get a tougher material. This is moulded with minimal room for expansion, therefore the number of bubbles is reduced. On the other hand, the top part is used for shock absorption. Hence, a small portion of the material is used and allowed to expand, giving a soft layer on the top of each sole. The result of this technique is an extended life and greater comfort with a lightweight sole.

10.2. EVA Soles

EVA soles are quite popular in the cheap footwear applications. EVA soles are so popular because its suitable properties like light weight, easy to mould and glossy finish but they are even too soft for some of the applications and it

Figure 15- EVA Sole
deforms easily over a time. EVA is a very flexible material and it is shaped by injection moulding like other thermoplastic polymers.

10.3. PVC Soles

The soles are often made of polyvinylchloride (PVC) material. They are the most popularly used worldwide for its versatility at the time of use, whether as for its lower price compared with other thermoplastic materials. It is commonly used (construction, metalworking, maintenance companies etc.) On the other hand they are heavier compared to the other materials. Besides, a common problem for many PVC soles is stickiness under hot conditions.

10.4. Soles’ Injection Moulding Machine

Currently, there are several companies which offer a choice of injection moulding machines to make soles. These machines are quite sophisticated, for example the next one has a LCD touchable setting with a display on the computer screen, which makes it easy to operate and monitor the state and condition of the machine. This machine has effective electronic controlling which allows adjusting and setting different PU injection volume for each station to meet different request of mould. Also, after injecting is finished it can clear residue automatically and PU material tank has stable thermos and stirring [29].

*Figure 16- Rotary Type Automatic PU Single Density Injection Moulding Machine*
10.4.1. Example of Automatic Machine of Thermoplastic Polyurethane

Brand: KingKong (from China). The price of this injection machine is about 50,000 dollars and it has a capacity of production of 200 pairs of soles per hour. Some of the specifications are shown in the next table [29]:

**Table 3- Specifications of Injection Moulding Machine**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>nº of station</td>
<td>15</td>
</tr>
<tr>
<td>Price</td>
<td>50000-100000 dollars</td>
</tr>
<tr>
<td>Moulds</td>
<td>500-1000 dollars</td>
</tr>
<tr>
<td>Capacity of production</td>
<td>200 pairs/hour</td>
</tr>
<tr>
<td>Injection pressure:</td>
<td>30/40 tons</td>
</tr>
<tr>
<td>Subjection force:</td>
<td>45x2 tons</td>
</tr>
<tr>
<td>Weight of the machine</td>
<td>12 tons</td>
</tr>
<tr>
<td>Energy</td>
<td>5 KW</td>
</tr>
<tr>
<td>Weight of the injection:</td>
<td>118, 138, 168</td>
</tr>
<tr>
<td>Shot size</td>
<td>130 155 190 cm³</td>
</tr>
<tr>
<td>Injection</td>
<td>160 g/s</td>
</tr>
</tbody>
</table>


11. The Market Analysis

In order to open a new line production in Spain, the Shoes’ market analysis will give an overview about the economic viability of this commercial activity in this region.

The shoe has historically been considered as a product of first need, therefore this production has always been closely linked to the needs of the different human groups worldwide. The footwear industry is also developed in a lot of countries around the world. Nowadays this activity not only persists in the developed countries but has gained particular strength in the economies emerging [30].

During the twentieth century, and especially since the early years of the second half, the footwear industry developed strongly in major Western European countries. Easter Europe, major Asian countries (China, Hong Kong, Korea, Indonesia and Taiwan) and Brazil reached this development few years later. These countries, with a comparably low labour cost, gained strength in the international market thanks to the migration of the production plants there, the transfer of knowledge and technology and the support of the local governments. They especially reached a high production in the markets of sport shoes and massive consumption.

Since the mid 80’s, the global footwear industry is has undergone a change of its production processes and work organization which allowed to increase the production significantly. But the evolution of this industrial not only was quantitative, the evolution of the industry generated a radical change in the competitive conditions and it affected to the stakeholders of this market, especially to the traditional European producers who had to adapt themselves to compete with the new mass production flows.

Among the various factors that led the transformation of the competitive situation over the last twenty-five years include the following points:

- Changes in the needs and shopping habits and consumption of customers’ groups, combined with the growing importance of the factor “fashion and novelty”. Implication of the companies in terms of innovations, design and life cycle product.
- Globalization is an essential factor. The major brands of sportswear, including sport shoes moved their industrial processes to emerging countries, whose working and environmental conditions, environmental, etc allowed them to be more competitive in international markets. Besides, the agreements of the World Trade Organization and the gradual removal of the barriers resulted in an increasing of international flows.
- The globalization process has extended thanks to the extraordinary development of communication and information technologies, which had an effect on consumers, but
also in industry. It enables new ways of operating in international markets. Also the development of production technologies, which introduced the microelectronics and computing, allows to achieve a significant progress in the automation degree of the machinery.

11.1. Producers

The global footwear production in 2010 reached 2 billion pairs. Manufacture of footwear is heavily concentrated in Asia, as can be seen in Figure 17, this continent now produces 87% of all the pairs of shoes produced worldwide [31].

![Figure 17- Distribution of Footwear Production by Continent in 2010](image)

Currently, the world’s leading footwear producers are, in this order, China, India, Brazil and Indonesia. Only China produces 62% of the world production. The Top 10 Producers account for 90% of the world footwear production.
Contrary to what might be expected, the major exporters of shoes do not match with the major producers. China is the dominant country in both aspects but an important part of the production of India, Brazil and Indonesia is being absorbed by their own markets. This is mainly due to the fact that they did not yet achieve the levels of price and quality to be able to compete on the international market.

Within the EU the production is concentrated in some industrial regions like Comunidad Valenciana (Spain), Véneto, Marche, Toscana and Apulia (Italy), Pays de la Loire (France) and in the north of Portugal. The percentages of production by countries in EU are:

**Figure 18- Distribution of Shoe’s World Production by countries in 2010**

**Figure 19- Distribution of Shoe’s Production in Europe in 2011**
11.2. Exports

The origin of exports is heavily concentrated in Asia, with 85% of the world total (Figure 20). However, in this case, Europe comes in second place representing 11%, with no other continent reaching more than 1%.

*Figure 20 - Distribution of Footwear Exports by Continent of Origin 2010*

Currently, China sells 73% of the 13 billion pairs exported worldwide. China has an even greater share of the exports than it has of the production, almost three out of every four pairs of shoes exported worldwide come from this country. These figures do not even include the exports of the Chinese special administrative region of Hong-Kong, itself the world’s second largest exporter country, with a share of 3%. Three other Asian countries, Vietnam, Indonesia and Thailand, are also among the world’s top 10 exporters in terms of volume. The list is completed by four European countries, Italy, Belgium, Germany and the Netherlands, all of them members of the European Union, and one South American country, Brazil.
11.3. Imports

As a continent, Europe leads the ranking of world importers, followed by North America. Seven out of the top 10 importers are located in this continent that is the destination of 43% of the world imports.
The largest importers in the world by countries are USA, Japan, UK and Germany. Spain is in the seventh place in the ranking.

11.4. Customers’ Analysis

In this case, the customers will be the enterprise that produces shoes and they need to buy the soles. Spanish footwear industry is the second most powerful in Europe, after Italian, thanks to the good quality of their products and the high production levels (200k pairs p/a) and thus 70% of the production is exported.

The sector of shoes in Spain is made by 2800 firms. This sector employs 47000 workers in Spain. Two thirds of the production and the employment are placed in the region of Valencia. These companies are mostly small or medium enterprises (SMEs) and even microenterprises and they are concentrated in certain regions, industrial districts, the most important being located in Alicante province.

Valencia is the centre of the important Spanish footwear industry, although it is also present in areas such as Castilla La Mancha and La Rioja. Over the last five years the Spanish industry has been able to increase its exports to the most important European markets, with the exception of the United Kingdom, but lost share in the USA, Japan and other non-European markets. At
the same time imports grew rapidly, both from China and from prestigious European markets such as Italy and France.

In order to enter to this sector it is important to analyse the Spanish industry at look for the opportunities and also some possible threats of the international market [30].

Table 4- SWOT Analysis of Spanish Shoe’s Industry

<table>
<thead>
<tr>
<th>Strength</th>
<th>Weakness</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Spain is the second producer in EU</td>
<td>- Preference to consume national products during a crises period</td>
</tr>
<tr>
<td>- The Spanish shoes are known as good quality products</td>
<td></td>
</tr>
<tr>
<td>- Design and originality</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Recently demand of creative and original product</td>
<td>- Increase of the international concurrence</td>
</tr>
<tr>
<td>- Labour</td>
<td>- The market is close to the capacity</td>
</tr>
</tbody>
</table>

The Spanish shoes’ producers usually copy and adapt some ideas from others (especially Italian producers) and they follow the tendencies of the market. This strategy of imitation has led them to achieve a good ratio quality-price.

The next table show the percentage of each type of shoes that were exported and imported in 2010.

![Figure 24- Types of Footwear Traded in Spain 2010](image-url)
11.5. Concurrence Analysis

It is important to know which companies are the concurrence and, also, their competitive advantages. In Spain there are around 250 companies who produce soles of shoes. Most of them produce soles made of PU and EVA. These companies are also concentrated in the region of Valencia, more specifically in Alicante.

11.6. Strategy

It is a brief but essential concept that set the course of the company. The strategy is based on the objectives, resources and the market research. Companies must choose between two possible strategies:

- **Cost Leadership**- it consists in being at the top of the list in terms of cost.
- **Differentiation**- it consists in creating an added value product to be perceived in the market as unique: design, image, customer service, home delivery, etc.

In that case the strategy is based in the differentiation. There are a lot of companies who produce shoe soles but very few who offer the possibility of choose modern colours for the sole [32]. Currently, the fashion of colourful soles is starting, only some brands offer this. And most of them are expensive marks. For example this pair of shoes is from a Britannic brand called Kurt Geiger and the price is around 200 Euros. Using the soles the designer wanted to keep the classic style while giving to the shoes a pop touch. The colour shoes are very versatile to improve the style of the shoes.

*Figure 25- Coloured Sole of Polyurethane*
III. Calculations

1. Economic Value

This part contains the study of the economic feasibility of this project, which consist in opening a new line production of shoe soles in Spain.

The cost of the project varies depending on which country the manufacturing line will be open. In that case the average prices in Spain will be used. The labour cost in Spain within the industry is 21 euros per hour.

There are several parameters that can define an investment, three of them are:

- Payment of investment (K): is the number of units that investors must pay to achieve that the project becomes operational.
- Project lifetime (n): is the estimated number of years which generates investment returns.
- Cash flow (Ri): it is the difference between the receipts and the payments, whether ordinary or extraordinary, in each of the years of the project life.

First of all, it is necessary to know how many pairs of shoes will be produced in one year, in order to know how much material is needed. The machines (as shown in paragraph 10.4) can produce 200 pairs of shoes in one hour. If there are two machines, at the end of the year 832000 pairs of soles will be produced:

\[
2 \text{ machines} \cdot 200 \frac{\text{pairs of soles}}{\text{h} \cdot \text{machine}} \cdot 8 \frac{\text{h}}{\text{day}} \cdot 52 \frac{\text{weeks}}{\text{year}} \cdot 5 \frac{\text{days}}{\text{week}} = 832000 \frac{\text{pair of soles}}{\text{year}} \quad (1)
\]

Besides, each injection shoot uses 138g of polyurethane. Therefore, a pair of soles needs approximately 276 (138x2) g. It means than it will be necessary 229632 Kg of TPU and 20% extra of PU for overshoot in the injection moulding and other kind of trouble-shooting. The total amount of material will be 275558,4 kg of plastic material per year.

Furthermore, the mould release agent has to be considered. In this case, a water-based mould release agent will be used because its good performance with polyurethane. Besides, this choice will avoid having annoying odours for the final users of the shoes. The price of it is approximately 3589,75 EUR per ton. This product is recommended to be 30-150 times diluted in water before spraying into the mould. If we consider that the layer of the mould release agent is about 20μm and the surface of a shoe sole mould of medium size is approximately
436.4cm². The volume of the mould release agent needed for each moulding injection will be 872.8x10⁻⁹m³ (436.4x10⁻⁴m² x 20x10⁻⁴m), but considering that 30% will be missed during the application, the volume per mould will finally be 1134.64x10⁻⁹m³. The density of the mould release agent is very similar to the water density, therefore for one pair of soles we will need (2x1134.64x10⁻⁶) kg of mould release agent. But considering than the product will be 100 times diluted in water, we will need to buy 2269.28x10⁻⁸ kg per sole of shoes. In one year we will need 1.89 Kg of mould release agent.

The colorant within the thermoplastics should vary from 2-5% of the total weight. Considering 3% of colorant, for 0.97 Kg of PU there will be 0.03 kg of colorant [29]:

\[
\text{Kg of PU} \text{ year} \cdot \frac{0.03 \text{ Kg of colorant}}{0.97 \text{ Kg of PU}} = 8522.43 \text{ Kg colorant/year} \quad (2)
\]

The price of the electricity in Spain varies depending on the consumption and on the section of the day. An approximated price of 0.1495 euros / kWh will be used in the calculations considering that the machines will work from 8:00 a.m. to 16 a.m., and that the consumption will be higher than 10kW. The cost of the electricity will be [33]:

\[
2 \text{ machines} \cdot \frac{5 \text{ Kw}}{\text{ machine}} \cdot 8 \frac{\text{h}}{\text{day}} \cdot 5 \frac{\text{days}}{\text{week}} \cdot 52 \frac{\text{weeks}}{\text{year}} \cdot 0.1495 \frac{\text{€}}{\text{kWh}} = 3109.6 \text{ EUR/year} \quad (3)
\]

In order to calculate the labour cost, the average price will be used (21 EUR/h). Considering that there will be two machines and every machine only needs one worker, there will be two employees. The labour cost for one year will be:

\[
2 \text{ workers} \cdot 21 \frac{\text{EUR}}{\text{h x worker}} \cdot 8 \frac{\text{h}}{\text{day}} \cdot 5 \frac{\text{days}}{\text{week}} \cdot 52 \frac{\text{weeks}}{\text{year}} = 87360 \text{ EUR/year} \quad (4)
\]

The first month there will be an extra labour cost in order to have the novel equipment set and fitted. It is considered that it will be necessary two days to start producing. The extra labour cost is calculated in the next equation:

\[
2 \text{ workers} \cdot 21 \frac{\text{EUR}}{\text{h x worker}} \cdot 8 \frac{\text{h}}{\text{day}} \cdot 2 \text{ days} = 672 \text{ EUR} \quad (5)
\]

Finally, the maintenance cost, which will include the products to clean the moulds, will be calculated considering that the maintenance of the machines takes one hour per day. Hence, the cost will be 546 EUR/year.
Payment of investment

The payment of investment includes the purchase of two injection moulding machines and the aluminium moulds. It also includes the local renting, the electricity and the material needed for the production of the soles during the first six months, because it is considered that the first months there will not be receipts.

<table>
<thead>
<tr>
<th>Product</th>
<th>Set</th>
<th>Price</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Moulding Machines</td>
<td>2</td>
<td>36579,09 EUR</td>
<td>73158,18 EUR</td>
</tr>
<tr>
<td>Aluminium moulds</td>
<td>30</td>
<td>365,67 EUR</td>
<td>10970,1 EUR</td>
</tr>
<tr>
<td>Material (TPU)</td>
<td></td>
<td>137779,2 kg/6months</td>
<td>0.6407 EUR/ kg</td>
</tr>
<tr>
<td>Colorant</td>
<td></td>
<td>4261,22 Kg/6months</td>
<td>1,68 EUR/kg</td>
</tr>
<tr>
<td>Mould Release Agent</td>
<td>0,945 Kg</td>
<td>3,59 EUR/Kg</td>
<td>3,39 EUR</td>
</tr>
<tr>
<td>Rental</td>
<td>1</td>
<td>800 EUR/month x 6 months</td>
<td>4800 EUR</td>
</tr>
<tr>
<td>Deposit of the Local</td>
<td>1</td>
<td>1200 EUR</td>
<td>1200 EUR</td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
<td>259,13 EUR/month x 6 months</td>
<td>1554,8 EUR</td>
</tr>
<tr>
<td>Labour</td>
<td>2 workers (6months)</td>
<td>21840 EUR/( worker</td>
<td>43680 EUR</td>
</tr>
<tr>
<td>Extra Labour Cost</td>
<td></td>
<td>672 EUR</td>
<td></td>
</tr>
<tr>
<td>Maintenance</td>
<td></td>
<td>273 EUR</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>231745,44 EUR</td>
</tr>
</tbody>
</table>

The payment of investment will be 231745,44 EUR.
Cash Flow

The production cost of one pair of soles will be the total payments of one year (290874,82 EUR) divided between the number of pair of soles produced per year (83200 pairs) = 3,5 EUR. The price of the sole shoes will be 5 EUR.

<table>
<thead>
<tr>
<th></th>
<th>set</th>
<th>Price/set</th>
<th>Total (EUR/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymeric material</td>
<td>275558,4kg/year</td>
<td>0,6407 EUR/kg</td>
<td>176550,27 EUR</td>
</tr>
<tr>
<td>(TPU)</td>
<td>275558,4kg/year</td>
<td>0,6407 EUR/kg</td>
<td>176550,27 EUR</td>
</tr>
<tr>
<td>Colorant</td>
<td>8522,43 kg/year</td>
<td>1,68 EUR/kg</td>
<td>14317,68 EUR</td>
</tr>
<tr>
<td>Mould Release Agent</td>
<td>1,89 Kg/year</td>
<td>3,59 EUR/kg</td>
<td>6,79 EUR</td>
</tr>
<tr>
<td>Rental</td>
<td>1</td>
<td>800 euros/month x 12month</td>
<td>9600 EUR</td>
</tr>
<tr>
<td>Labour</td>
<td>2 workers</td>
<td>43680 EUR/year x worker</td>
<td>87360 EUR</td>
</tr>
<tr>
<td>Electricity</td>
<td>2 machines</td>
<td>3109,6 EUR</td>
<td></td>
</tr>
<tr>
<td>Maintenance</td>
<td></td>
<td>546 EUR</td>
<td></td>
</tr>
<tr>
<td>Total payments</td>
<td></td>
<td>291490,34 EUR</td>
<td></td>
</tr>
<tr>
<td>Sale of soles</td>
<td>83200</td>
<td>5 EUR</td>
<td>416000 EUR</td>
</tr>
<tr>
<td>Total Receipts</td>
<td></td>
<td>416000 EUR</td>
<td></td>
</tr>
<tr>
<td>BENEFITS (Receipts-Payments)</td>
<td></td>
<td>124509,66 EUR</td>
<td></td>
</tr>
</tbody>
</table>

With the benefits of 124509,66 EUR per year, after 9 months of production the investment of 231745,44 EUR will be recovered.

Nevertheless, it is possible to have the investment return faster if production is duplicated. It will be possible by producing also during the evening. In this case, two workers more will be needed and they will receive a higher salary during the evening because the labour cost would increase 35% between 22:00 p.m. and 6:00 a.m. On the other hand if the factory works during the night, the cost of electricity is 56% reduced. The receipts per year will be the double (832000 EUR) and the payments per year will increase 310724,96 EUR, as shown in the table 5. Therefore, the new benefits per year will be 229784,7 EUR.
Besides, the amount of the investment will also increase because of the cost of the materials, labour and electricity of the evening turn during the first six months (see in table 6).

The total investment will be 387107,91 EUR, and the benefits per year will increase 84% (229784,7 EUR/year). The investment return will be achieved after 5 months of production.

<table>
<thead>
<tr>
<th>Table 5- Payments for the Evening Turn per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 workers (evening turn)</td>
</tr>
<tr>
<td>Electricity</td>
</tr>
<tr>
<td>Material TPU</td>
</tr>
<tr>
<td>Colorant</td>
</tr>
<tr>
<td>Release Agent</td>
</tr>
<tr>
<td>Maintenance</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 6- Increase of the Investment due to the Evening Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour cost</td>
</tr>
<tr>
<td>Electricity</td>
</tr>
<tr>
<td>Material TPU</td>
</tr>
<tr>
<td>Colorant</td>
</tr>
<tr>
<td>Release Agent</td>
</tr>
<tr>
<td>Maintenance</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>
2. Mechanical calculations

In order to make the mechanical calculations, the shoe sole will be considered as a rectangle with the dimensions $T(254 \text{ mm}) \times L(30 \text{ mm}) \times h(100 \text{ mm})$. It will also be considered that the material does not cool while filling and that it behaves similarly to a Newtonian-like fluid.

![Figure 26- Dimensions of the Mould for Calculations](image)

2.1. Filling Pressure

In this paragraph the minimum pressure at the gate in order to fill the mould is calculated. In other words, it is the drop pressure from the entrance until the farthest point of the mould. The Injection pressure ($P_{\text{min}}$) for a given flow rate can be determined from non-Newtonian flow expression. If the fluid is modelled by the Power-law (9.2), the pressure drop can be calculated by using the next equation [20]:

$$P_{\text{min}} = \text{Pressure Drop} |\Delta P| = \frac{2K}{h} \left[ \frac{(2n+1)2Q}{nTh^2} \right]^n$$

(5)

And for Newtonian fluids ($n=1$)

$$P_{\text{min}} = |\Delta P| \approx \frac{12\mu LQ}{Th^3}$$

(6)

For the injection moulding process the shear rate goes approximately from $10^3$ to $10^4$ s$^{-1}$. Unprocessed TPU shows a viscosity of is $10^{2.6}$ (Pa.s) when the shear rate is $10^3$ (Figure 27). The
injection speed in the shoe sole machine is 160 gr/s (10.4), assuming that the density of the melt polyurethane is approximately 1.15 gr/cm³ the volume flow rate (Q) will be:

\[ Q = \frac{160 \, \text{gr}}{s} \cdot \frac{1}{1.15} \, \text{cm}^3 \cdot \text{g} \cdot 10^3 \, \text{mm}^3 \, \text{cm}^3 = 139130.43 \, \frac{\text{mm}^3}{s} \] (7)

Using the equation 6, the minimum pressure to fill the shoe sole mould is:

\[ P_{min} = \frac{12.10^{2.6} \, (\text{Pa.s}) \cdot 254 \, \text{mm} \cdot 139130.43 \, \frac{\text{mm}^3}{\text{cm}^3}}{30 \, \text{mm} \cdot (100 \, \text{mm})^3} = 5627.50 \, \text{Pa} \] (8)

Nevertheless, this pressure usually is not enough to fill the mould and it is necessary to apply an additional pressure to compact the material and to counteract the shrinkage. Therefore, the filling pressure will be hold on up to 2xPmin= 11255.01 Pa.

Besides, thermoplastic polyurethane often behaves as a shear-thickening. Therefore, the require pressure to fill the mould will be calculate with an extra of 40% in order to counteract the increase of viscosity [34].

Total fill pressure: 11255.01 Pa x 140% = 15757.01 Pa = 15.76 KPa

![Figure 27 – Typical Viscosity of Polyurethane depending on the Percentage of Additives](image)
### 2.2. Clamping Force

The clamping force is the force that the mould injection machine applies to the mould in order to keep the mould securely closed when the plastic material is injected. Clamping force must be higher than injection force. The injection moulding machines are usually characterized by the tonnage of clamping force that they provide. It is possible to apply this clamp pressure with hydraulic or mechanical toggle [35].

The force needed to keep closed a part of a mould with dx of length is the product of the pressure with the area [20].

\[ \delta F = P \delta A = P \cdot T \cdot dx \quad (7) \]

And the total force will be:

\[ F = \int_0^L P \cdot T \cdot dx \quad (8) \]

If the pressure at the gate is \( P_g \) and assuming that the pressure is linearly distributed as in the equation 9:

\[ P_x = P_g - \frac{x}{L} |\Delta P| \quad (9) \]

Then,

\[ F = T \int_0^L \left[ P_g - \frac{x}{L} |\Delta P| \right] dx = T \left[ P_g L - \frac{L |\Delta P|}{2} \right] = TL \left[ P_g - \frac{|\Delta P|}{2} \right] \quad (10) \]

If the minimum pressure is applied ( \( P_g = P_{min} = |\Delta P| \) ) the clamping force is:

\[ F = TL \cdot \frac{P_{min}}{2} = \frac{254 \text{mm} \cdot 30 \text{mm} \cdot 15757.01 \text{Pa}}{2} = 60.03 \text{ N} \]

In other words, the clamping force can be calculated from the following formula:

\[ \text{Force} = \text{Projected Area} \times \text{Average Pressure} \]
3. Shoe Sole Design

Shoe sole must be functional and comfortable. Foot structure is complicated; therefore, shoe sole design requires to satisfy ergonomics.

During exercise, like running or other sports it is important that the sole protects our foot from absorbing huge force. On one hand the outsole design should increase the hardness in order to prevent the sole from the abrasion, and on the other hand the midsole design should be lighter to improve the shock absorption. Nevertheless, for casual shoes it is not necessary combine different layers because the impact on the soles is less heavy.

Nowadays, there is a wide offer of footwear CAD/CAM. These tools provide a solution that includes 3D concept design and sole engineering, 2D pattern development, patter cutting and costing. Software tools specifically developed for the footwear industry are intuitive solution for 3D and the use of these tools helps to reduce the product time to market.

Nevertheless, these products are generally expensive and only big companies can afford them. For this projects two different soles has been design by using CAD software Solidworks. This tool allows the user to create complex designs and to make mechanical simulations.

The two soles are made from the same material (TPU), but they have different functionalities. The first one is a sole for a classic shoe, which would be used for walk in flat, hard pavements. Contrarily, the second sole is thicker and the design is thought to move better on grass or other soft materials. This kind of sole is also used in places where the weather is quite cold, hence the soles must have grooves in order to do not slide on icy surface. Both soles have been designed considering that they will be used in a shoe of the European size 41 (size 9 for UK).

Figure 28- Classic Shoe with Smooth Sole

Figure 29- Boot with Wrinkled Sole
3.1. Classic Shoe Sole Design

SolidWorks allows the user to modify the appearance of the part that it is being designed. In this case the yellow colour has been chosen to simulate the appearance of coloured TPU.

![Figure 30- Isometric View of Classic Shoe Sole Design](image)

<table>
<thead>
<tr>
<th>Mass</th>
<th>0.15538 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volum</td>
<td>0.000155375 m³</td>
</tr>
<tr>
<td>Density</td>
<td>1150 kg/m³</td>
</tr>
<tr>
<td>Weight</td>
<td>1.75108 N</td>
</tr>
</tbody>
</table>

3.2. Boot Sole Design

![Figure 31- Isometric View of Boot Sole Design](image)

<table>
<thead>
<tr>
<th>Mass</th>
<th>0.382603 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volum</td>
<td>0.000332698 m³</td>
</tr>
<tr>
<td>Density</td>
<td>1150 kg/m³</td>
</tr>
<tr>
<td>Weight</td>
<td>3.74951 N</td>
</tr>
</tbody>
</table>
3.3. Mechanical Simulations

To do the simulations in Solidworks it is necessary to choose the materials of the parts. The mechanical properties of the material are showed in the next table, this data has been taken from PEARLTHANE® TPU, which is a thermoplastic polyurethane which is used for extrusion and injection [36]:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1150</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>11760000</td>
<td>N/m²</td>
</tr>
<tr>
<td>Limit of Elasticity</td>
<td>24.10⁶</td>
<td>N/m²</td>
</tr>
</tbody>
</table>

The simulations made with Solidworks consist in fixing some parts of the sole and applying the force that a person who weighs 80 kg would transmit to the surface of the sole. It is considered that the whole weight is applied on one sole. When the person is walking, there is a period of time while one foot is not touching the ground; therefore the whole weight is supported by one shoe.

Simulation 1- Boot Sole

Subjections and Forces

25 Surfaces of the sole have been fixed for this simulation. These surfaces have been chosen because they are closer to the ground and they will be in contact with it before the others. The force is 800 N, which is applied equally in the up surface and perpendicularly to it.

![Figure 32- Subjections and Forces of Simulation 1](image)
Mesh details

The mesh of this simulation is made up by 23214 high order quadratic elements, their size is 5.2 mm. The tolerance of the Mesh is 0.260024 mm. And it contains 37742 nodes.

Results

The von Misses stress of the different elements of the sole can be observed in the Figure 35. The simulation shows different colours on the elements depending on the value of the stress supported by each one.

The limit elastic of the material is $24 \times 10^6$ N/m² and none of the elements are close to reach this value. The maximum stress suffered by an element is $2.14156 \times 10^6$ N/m². The minimum stress is 390.438 N/m². As can be seen in the figure 35, the dark blue elements suffer less stress and they appertain to the thicker parts of the sole. Contrarily, the parts of the sole that are thinner suffer the maximum stress.
When the weight of the person is applied on the surface of the sole, the sole will tend to be in full contact with the ground. Therefore, the biggest displacements will correspond to the parts which are more far from the ground in the initial state, when there is no strain in the sole. As can be in the Figure 36, the highest values of displacement are in the middle part of the sole and in the tip of the sole. The maximum displacement in the simulation is 32.63 mm and the node is located in the tip. However, the minimum displacement is 0 and it corresponds to the fixed surfaces. These surfaces simulate the parts that are in contact with the ground when none effort is applied, therefore their displacement is impeded by the ground.

**Figure 35- Von Mises Stress of Simulation 2**

**Figure 36- Resultant Displacement of Simulation 1**
It can be observed that the biggest deformation is in the toes. The middle part of the sole also suffers high stress and displacement. Nevertheless, the deformation is small and the sole can hold the weight of a person. The results also show that the sole is very flexible, which is important for the comfort of the person who is wearing the shoe.

Simulation 2- Simplified Classic Shoe

For this simulation, the form of the classic sole has been simplified in order to have a better contact between the sole and the ground. It is more realistic than the previous simulations because the soles cannot cross the plane of the ground. It has been also considered that the weight is applied only on the footprint. The mass of this new model is 0.279944 kg and the volume is 0.000243429 m$^3$. 

Figure 37- Deformed Shape of Simulation 1

Figure 38- Isometric View of Simplified Model

Figure 39- Profile View of Simplified model
Subjections and Forces

A pressure of 3500 N/m² has been applied on the foot print. In this simulation only one edge of the sole has been fixed: the edge of the hell which is in contact with the floor. The surfaces that are in contact with the floor only can move over this plane.

![Figure 40- Pressure Applied on the Foot Print](image)

![Figure 41- Fixed Edge and Slider Surfaces](image)

Mesh

The mesh of this model is made up by 17466 nodes and 10600 elements.

![Figure 42- Mesh of the Simulation 2](image)

Results

The maximum value of stress reaches 52055.3 N/m². Besides, the highest stresses are concentrated in the middle of the sole, where there is no contact between the bottom of the sole and the ground. The maximum value of stress is much smaller than in the first simulation, which was 2.14156x10⁶ N/m², this is due to the fact that the bottom surface of the sole has a better contact with the ground and the stress is more distributed over the sole. The minimum stress is 29.3932 N/m².
The biggest displacements are also in the middle of the sole, which can be seen in the Figure 44 and the maximum value is 0.20031 mm. It can be observed that the part of the toes shows bigger displacement than the hell because the subjection in the simulation has been applied in an edge of the hell.

TPU is tough enough to support the weight of one person and at the same time it gives the flexibility necessary to allow the movement of the foot when people are walking. The weight of the classic shoe sole is 155 gr. This is a light sole and it will be comfortable for the users. Contrarily, the boot sole reaches 383 gr, which is too heavy. Therefore, for thick soles, it would be better to use a material with a lower density, such as polyurethane foam.
4. Mould Design

The mould of the sole will consist from two components, the injection mould and the ejector mould. The injector mould is fixed during the process. Besides, this part contains the gate through which the plastic enter the cavity. It also contains some channels in order to allow the molten plastic to flow from the barrel into the mould. When the mould is open the moulded part remains on the ejector side of the mould. Then, the ejector pins, also known as knockout pins, push the finished moulded product out of the mould.

The moulds contain releasing holes, which allow the air to go out from the mould while the material is injected. The diameter of the holes is 1 mm and their disposition is shown in the mould drawing (Annexe 1 and 2).

In order to keep the mould closed during the injection moulding process two latch clamps will be put on the mould. A lot of companies offer this kind of lock which is a simple and cheap way to ensure that the mould will remain tightly close. The drawings of the latch clamp chosen for the sole moulds can be seen in the Annexe 3.

![Figure 45 - Injectors Sides of the moulds](image1)

![Figure 46 - Ejector Sides of the moulds](image2)
The surface of the two parts or the mould that are in contact when the mould is close have to be perpendicular to the direction of the clamping force. The shrinkage of the material must be taken into account when determining the draft required.

### 4.1. Diameter of the gate

In order to calculate the diameter of the gate, the next equation will be used [37]:

\[ \dot{\gamma} = \frac{32 \cdot Q}{\pi \cdot D^3} \quad (11) \]

Where:

- \( \dot{\gamma} \): Shear Rate
- \( Q \): Volume Flow rate
- \( D \): Diameter of the gate

Using a shear rate of 10\( \times 10^3 \) and the volume flow rate calculated in the part 2.1 (139130.43 mm\(^3\)/s) the diameter of the gate will be:

\[ D = \sqrt[3]{\frac{32 \cdot Q}{3.14159 \cdot \text{Shear Rate}}} = \sqrt[3]{\frac{32 \cdot 139130.43 \text{ mm}^3/\text{s}}{3.14159 \cdot 10 \cdot 1000 \text{ s}^{-1}}} = 5.2136 \text{ mm} \quad (12) \]

### 4.2. Boot Sole Mould Design

The material that has been chosen for the mould is aluminium 2024, with a density of 2800 kg/m\(^3\). The dimensions of the mould are (300 mm x 126 mm x 65 mm). The total mass of the mould is 5,94816 kg (3.67848 kg in the ejector part and 2.26968 kg).

![Isometric View of the Boot Sole Mould](image_url)

*Figure 47 - Isometric View of the Boot Sole Mould*
One simulation has been made in Solidworks in order to check if the dimensions of the mould are the correct and if it can support the clamping forces. It consisted in applying the clamping forces (calculated in the Part 2.2.) on the top surface of the mould.

As can be seen in the Figure 48, the flat surface on the ejector mould has been fixed and the clamping force of 60 N has been applied on the other part of the mould. The mesh of the mould is made up by 23545 nodes and 14450 elements with a size of 12,8583 mm.

*Figure 48- Fixed Surface and Force on the Boot Sole Mould*

The maximum Von Misses stress in one node is 17018.1 N/m², which is small value compared with the elastic limit (75829100 N/m²). Therefore, the mould can support the clamping forces without being damaged. The maximum strain is $1.79389 \times 10^{-7}$ N/mm² and maximum displacement is $1.00929 \times 10^{-5}$ mm.

*Figure 49- Von Misses Stress in Boot Sole Mould*
4.3. Classic Shoe Sole Mould Design

The material for this mould is the same than in the first mould. The dimensions of the mould are (273mm x 106mm x 60mm). The total mass of the mould is 4.41998 kg (2.30486 kg related to the ejector part and 2.11512 kg to the injector part).

The force calculated in the mechanical study and applied in the first simulation (60 N) is insignificant compared with the clamping forces that the injection moulding machine can achieve. This is due to the fact that the model used for calculating the injection pressure has been highly simplified. When the mould has a complex shape, such as the grooves on the sole, the necessary injection pressure increases significantly, thus the clamping force also does. Therefore, in the simulations of the second mould instead of 60N, 500N has been applied in order to estimate if it could support the increased forces. The mesh of this simulation is made up by 16854 nodes and 10138 elements with a size of 11.6517 mm.

![Figure 50- Fixed Surface and Applied Force on Classic Shoe Mould](image)

As a result, the maximum Von Misses stress reaches 160156 N/m², which is still far from the elastic limit. The maximum strain also increased until 1.70596×10⁻⁶ N/mm² and as can be in the Figure 51, the maximum values are in the middle of the mould because, where both sides of the mould cannot touch each other because of the cavity.
As a conclusion, the aluminium can be considered as a suitable choice for the moulds of the soles because they can perfectly support the clamping forces. Alternatively, it would be necessary to use steel, which will increase the costs significantly. Besides, steel moulds are made to last a long time but while the footwear industry is very fashionable and the moulds should be redesigned according to the tendencies.

**Figure 51- Strain Diagram of Classic Shoe Mould**
IV. Conclusions

Within the footwear industry it is very important to combine design and good quality. People use clothes and footwear as a sign of identity, therefore it is important to innovate in the design and to follow tendencies because they will feel identified with modernity. People are willing to spend more money in the shoes, because bad quality shoes can damage our health. Besides, the material of the shoe sole is one of the most important things to take in account when we buy a pair of shoes. This industry is constantly renovating, but good quality shoes will never be old-fashioned.

After analysing the two kinds of polymers that are mostly used in footwear industry (polyolefins and polyurethanes) the thermoplastic polyurethane (TPU) has been chosen to make the study of the production of shoe’s soles in Spain.

TPUs are largely used as high performance elastomer and tough thermoplastics in a great variety of applications. It has the high properties that a good performer shoe sole require as high impact strength, abrasion, solvent and oil resistance. This polymer is widely used in the footwear industry because it is more resistant to abrasion than other polymers, like polyolefins. It can be processed by commonly used techniques, such as extrusion and injection moulding.

Nevertheless, the calculations show that for a classic shoe TPU’s would be a good material while for soles that requires thicker dimensions this material would be to heavy and it would not be comfortable for the consumers. Therefore, each shoe sole should be made up of different materials depending on their requirements of the shoe and its design.

The initial investment needed to open the soles production line in Spain is 231745,44 Euros, which will be recovered after 9 months of production. Besides, this time would be improved if the factory produced also during evening time. In this case, the initial investment would be 387107,91 EUR and it would be recovered in 5 months. Moreover, the benefits per years would increase 84%.

The initial investment includes the machinery for the injection moulding and also the moulds. The moulds used for the soles are made of one aluminium alloy (2024). Steels moulds are used for big quality productions but in this case the small dimensions of the mould allow the use of aluminium because the clamping forces are quite low and the aluminium mould is fully able to
support them. Besides, if steel moulds were used they would have to be used a longer time in order to amortise the investment. Hence, this would be an impediment to be in constantly innovating and consequently to be strongly positioned in the market.

The discovered of the plastics has modified our life style and they were such and impact in societies that some moments of the XX century were called “the ERA of the Plastics”. Despite the large quantity of advantages of plastics, they also entail some problems. The excessive use of them has generated a lot of residues which are difficult to handle. In order to decrease the consumption of plastic, some habits are already changing on the people’s behaviour, like the use of our own bags for shopping and reusable plastic bottles and of course to separate the wastes in order to recycle.
DE-STA-CO® TOGGLE LOCK PLUS OPTION

Shown with optional Latch Plate (385102)

DIMENSIONS IN mm

<table>
<thead>
<tr>
<th>NAME</th>
<th>SIGNATURE</th>
<th>DATE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5-3-0314</td>
<td></td>
</tr>
</tbody>
</table>

latch clamp
Appendix 3
V. References

17. International Finance Corporation (IFC); (2007, April 30) “Guias sobre el medio ambiente, salud y seguridad para la fabricación de polímeros derivados del petróleo".


37. Barry Smith, J.; “Injection Moulding - Gates and Runners” (Copyright J. Barry Smith1999). Published for Plastics Consultancy Network