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ESCOLA TECNICA SUPERIOR ENXEÑARIA

PURSUING ENVIRONMENTAL SUSTAINABILITY IN THE VEHICLE PAINTING PROCESS IN VIEW OF COMPLIANCE WITH FORMALDEHYDE EMISSION LIMITS

MASTER ENVIRONMENTAL ENGINEERING

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CERTIFICADO

Prof. Dr. Gumersindo Feijoo Costa, Catedrático de Ingeniería Química de la Universidad de Santiago de Compostela; y **Daniel Granadero Rey**, Project Leader responsable de emisiones y permisos en la empresa de estudio,

certifican que:

Aida Isabel Garcia Muñoz ha realizado bajo su dirección el presente Trabajo de Fin de Máster **bajo compromiso de confidencialidad,** con título:

"Pursuing environmental sustainability in the vehicle painting process in view of compliance with formaldehyde emission limits".

Y para que así conste, firmamos el presente informe en Santiago de Compostela a 28 de Julio de 2017.

Sindo

Aida García

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ABSTRACT

The environmental impacts associated with the vehicle painting process of a European plant were investigated based on a life cycle assessment (LCA) gate to gate study.

Due the new hazardous classification of Formaldehyde, the studied plant carried out several measurements of formaldehyde emissions in order to detect and study those areas where the emissions were higher. As a result, some improvement actions were implemented and proposed to reduce these emissions.

The three main processes within the painting operations were studied. It was found that the higher contribution to the total impact is due to the Electrocoating and Top coat processes, being the Electrocoating materials and natural gas consumption the main cause.

Moreover, four different improvement Scenarios were studied for the company to reduce formaldehyde/VOC emissions and as a result, the impact on the human toxicity. LCA comparative study was performed for all of these Scenarios.

The Scenario A represents the current situation of the plant with some improvements already implemented that implies an increase of the natural consumption, thus increasing the total impact.

Scenarios B and C represent different abatement equipment possibilities to reduce air emissions on Top cat ovens. An environmental impact and economic analysis was developed. Scenario C was found the most environmental sustainable option because it includes a reduction on the natural gas consumption. However, both Scenarios achieve the formaldehyde emissions reduction and, as a consequence, the human toxicity impact could be reduced. Due to the fact that Scenario B is more economically favourable, the company decided this option for the air emissions reduction.

The last Scenario studied was a future improvement over the Scenario B. It was seen that this improvement would not improve the situation. Natural gas consumption increases the total impact despite of the reduction due to the VOC abatement.

In all cases natural gas consumption plays an important role at the whole plant and all the Scenarios studied increase their total impact due to that. Despite of this, as it was pursued, in all Scenarios there is a considerable reduction on the human toxicity impact.

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1. INTRODUCTION

Vehicle manufacturing is one of the most complex industrial manufacturing processes because it requires big spaces and high technologies. Within the whole process, coating and painting operations have the highest environmental impact [1]. These impacts are related to the use of energy and resources, water consumption and wastewater streams, generation and treatment of waste, and mainly, to air emissions. Painting processes release around 80-90% of the total VOC (Volatile Organic Compounds) emissions, which are generated due to the cleaning, coating and drying operations [1-3].

There are around 400.000 premature deaths per year in the EU due to elevated levels of air pollutants. Since the late 1970s reducing the effects of contaminants into the air and preventing potential risks to human health have been one of the main targets for the European Union. The emissions into the atmosphere of carcinogenic, mutagenic and toxic to reproduction substances are being reduced systematically by introducing legal requirements for their substitution and relevant emission limit values [4].

Life Cycle Assessment (LCA) is a very useful tool to analyse the environmental impacts from a product or process. There are several LCA studies related to the environmental impacts in the vehicle industry [5] but most of them are focused on new engines or electric cars [6]. However, likely because of the difficulties collecting data, there are not many LCA studies associated with the painting process. Papasavva et al. studied different coating materials commonly used in automotive painting, focusing on the use of powder paints as alternative to solvent-borne paints with the advantage of not containing solvent and being easily reusable [7]. Rivera et al. made an interesting research having into account the overall environmental problems of the paint shop studying metal and plastic surfaces. In that project, the areas with the greatest contribution to the environmental impact were identified. Moreover, potential alternatives for process improvement were proposed focused on reducing the energy consumption [3].

In 2015, the European Union through the CPL Regulation, decided to reclassify formaldehyde as possible carcinogenic [8]. Due to this recent European classification, the vehicle manufacturing companies in Europe are carrying out an exhaustive investigation in all its painting plants. Several measurements of formaldehyde emissions were performed at the most relevant areas. Having into account these measurements, the plant under study decided to reduce the emissions in those areas implementing some correctives actions. In this project, a LCA gate to gate study was carried out in order to analyse and compare the environmental impact of the different improvement actions implemented or considered to reduce the formaldehyde emissions at this painting facility.

1.1 Vehicle manufacturing process

High-volume passenger car industry is one of the major manufacturing industries in Europe. The whole process is carried out in different areas where most of the parts of the vehicle are produced, assembled, painted and completely finished to obtain quality and competitive vehicles.

The next picture shows a brief scheme of the whole process. The most important inputs for the entire plant are energy, materials and water as it is illustrated at the top part, and the main environment impacts from the manufacturing process are related to air and water emissions and to the waste treatment, represented as outputs at the bottom part of the picture.

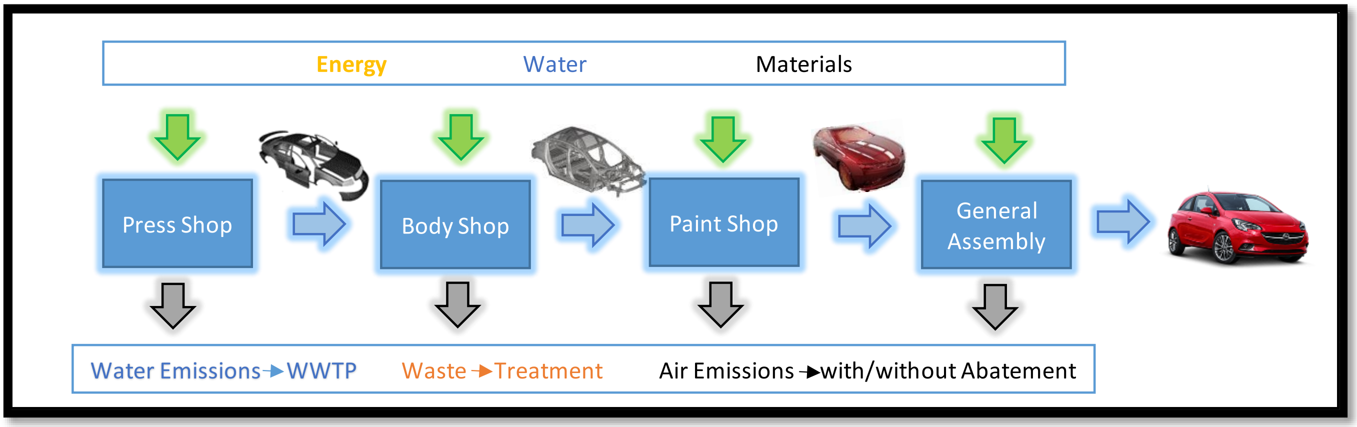

Fig. 1. Vehicle manufacturing process

As it can be seen in the picture, there are four important areas where the manufacturing process takes place:

- **Press shop:** It consists of a stamping and metal forming process where the vehicle shell shape and geometry is developed. The principal material is a coil of aluminium or steel which is taken to a stamping line to form the vehicular panels with different mechanical or hydric presses. There is a matrix cleaning process where an important amount of oily wastewater is generated. This stream is treated in a separated wastewater treatment plant (WWTP) [11-12].

- **Body shop:** It compiles all activities of joining to give shape and dimensions to the vehicle's shell. The resultant product of this part of the process is called body in white (BiW), which is the bodywork completely joined, ready to be painted [11].
- **Paint shop:** This is where the whole painting process takes place. The BiW goes through a sequence of different complex processes to ensure the adequate bodywork resistance. For that, it is necessary to apply different protective layers. This includes several painting steps, under body sealing, and PVC and vax applications [11]. The main focus of this work will be given to the painting process and thus a detailed explanation of this process can be seen in the next chapter.
- **General assembly:** It is the final area where all the parts of the car, more than 300 interior and exterior components, are joined to obtain the final product. Here, chemical wastewater is produced and later on treated with physical-chemical treatment processes at the WWTP [11-12].

1.2 Painting process

The vehicles are painted not only to obtain the desired appearance, but also a long-term protection against corrosion, weather conditions, chemical influence (e.g. bird droppings, acid rain), chipping, sun, abrasion in car washes, etc. must be guaranteed. This can only be achieved by application of several layers designed to complement each other. To ensure the efficiency of the process, those layers of paint must be applied and dried quickly by using high technology [2]. The next picture shows a scheme of the common whole painting process. Depending on the age and characteristics of the painting plant, the product, and other specific quality requirements, the painting steps could vary from those in the picture.

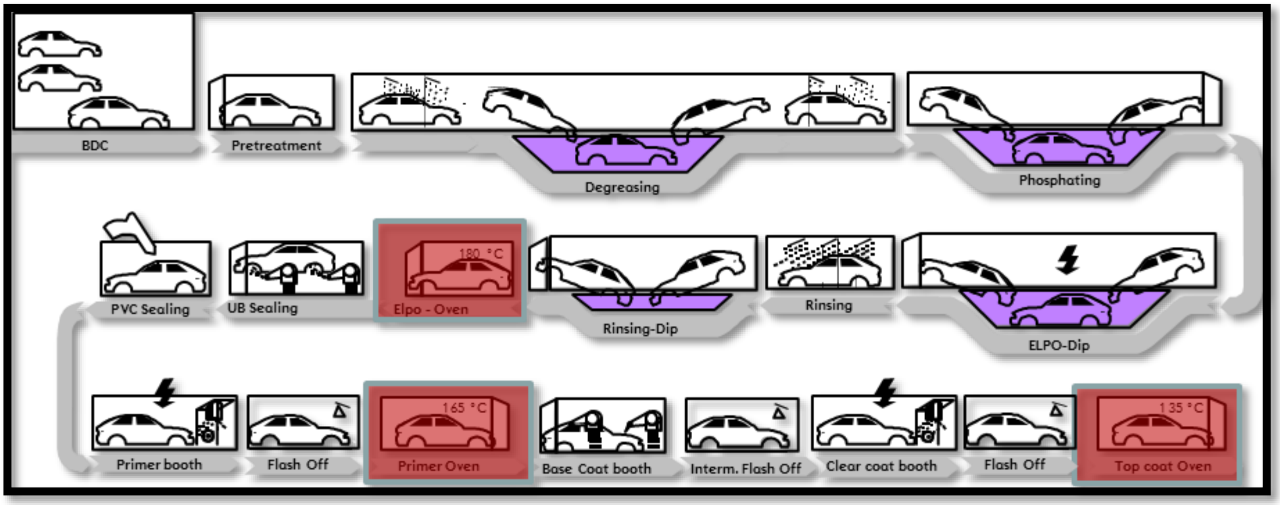

Fig. 2. Example of the main painting processes in a vehicle manufacturing painting plant.

The main steps in the vehicle painting process are pre-treatment, Electrocoating, PVC sealing, Primer coat and Top coat.

1.2.1 Pre-treatment.

The BiW comes from the press shop ready to be painted, but it needs a previous treatment to be prepared for the different paint layers.

First, the car is submerged into a cleaning aqueous solution to remove the dirtiness from the previous steps. After that, the degreasing step takes place for cleaning and to achieve a reactive surface that is able to form the next layer. Subsequently, the phosphating process is carried out, which consists of the application of a protective layer that gives the metal some anticorrosion, antiskid and anti-seize properties.

The sludge generated in this process has to be removed constantly by filtration techniques and the treated water is typically reused in the same process [11, 13, 14].

1.2.2 Electrocoating (ELPO-coat).

This process consists of dipping the vehicle body in an aqueous solution made of resins, pigments, additives and solvents and stabilise it by electrostatic forces. The metal surface acts as the cathode and the paint particles as the anode so that, when an electromagnetic field is created, the charged paint particles travel to the metallic vehicle body and are adhered in its surface.

As in all other processes, this step has to be continuously monitored to ensure a good performance. The most important control factors are: voltage and current density to create the electromagnetic field, bath temperature, pH, paint conductivity, amount of solids, and electrolyte concentration.

After the ELPO-coat bath there is a rinsing process with the same aqueous solution mixed with water to remove all the paint particles that have not been electrically deposited in the metal surface but could still remain on the bodywork panels.

To reduce paint losses, the multiple rinsing systems use ultrafiltration to regenerate solids and liquids. The high solids part is recirculated to the immersion bath reducing the amount of paint required and obtaining a closed loop.

Following the electrocoat treatment, a first drying oven is placed to dry and cure the applied paint films. The high temperatures needed to dry the paint release VOC from the paint. In order to reduce those emissions, usually an abatement installation is in place to treat the air streams. As a consequence of the incineration treatment, NOx and CO are released to the atmosphere.

The wastewater from the phosphating and electrocoat processes is treated before the WWTP. The treatment consists of pH adjustments followed of a neutralisation to stabilise the wastewater. [2, 11, 13, 14].

1.2.3 Under body sealant, PVC

The underbody sealant with polyvinylchloride (PVC) materials is usually applied after the E-coat process and before the Primer coat. It is applied in areas with a higher corrosion potential such as joints and seams. Depending on the installation, this step can be carried out by hand or robotic application systems, although both procedures are usually used. [2, 11, 13, 14].

1.2.4 Primer coat.

It takes places in a booth chamber where the first real paint film is typically sprayed by robots. The main targets to achieve by the Primer application are solve the possible slopes from the previous layer, Prepare the surface for the next paint coat application, achieve adhesion stability building a layer with the required thickness and quality and ensure a stone chip and UV radiation protection.

Inside the painting booth there is a constant air flow in descendent direction to remove the overspray and avoid the formation of bubbles or excesses.

After the paint spray application, there is a flash off area and following an oven to evaporate the solvents and dry the first paint layer. In both areas there are some considerable air emissions that are usually treated by an installed abatement system releasing NOx and CO [2, 11, 13, 14].

1.2.5 Top coat (Base-coat + Clear coat).

It is composed of two subsequent steps, the Base coat (BC) and Clear coat (CC) paint application. These processes provide different layers of paint to the vehicle to ensure the required results.

The function of the Base coat is to provide colour, effect and durability. There are a lot of different base-coat paints depending on the desired colour. Usually, the viscosity of the paint must be adjusted by adding water or solvent depending on its composition.

In each change of colour there are cleaning procedures with solvent to ensure that there are no rests of other colours inside the robots and to avoid contaminations. This action implies an important amount of solvent waste. Some plants send this solvent waste to an external company to be recycled and typically it is sold again to the painting plant to be reused.

Clear coat is used to protect the colour pigments from the environment, scratches and chemical aggressions. It is applied above the base coat when this is not completely dry so there is usually no oven after the base coat paint application. Instead, there is usually a small flash off area to remove water and solvents from the layer avoiding problems in the next process [2, 11, 13, 14].

The complete drying step for both coating layers takes place in a drying oven placed at the end of the Top coat process. The oven is usually operated at around 130°C. Again, there are air emissions at these parts of the painting process that have to be treated.

Under the painting booths in Primer, base coat and clear coat processes there are water scrubbers to collect the remaining paint. This wastewater mixed with waste paints is taken to the same water tank that contains coagulants in order to separate the water from the paints. This way, the water can be recirculated and used at the same system and the paint can be collected for its disposal.

1.3 Paints

As it was explained before, the whole process needs three different kinds of paints for the three main painting steps of coat application on the BiW; Primer, Base coat and Clear coat. Those paints have essentially the same principal components and different thicknesses are required. The next figure shows the different painting layers in a vehicle and its required thickness.

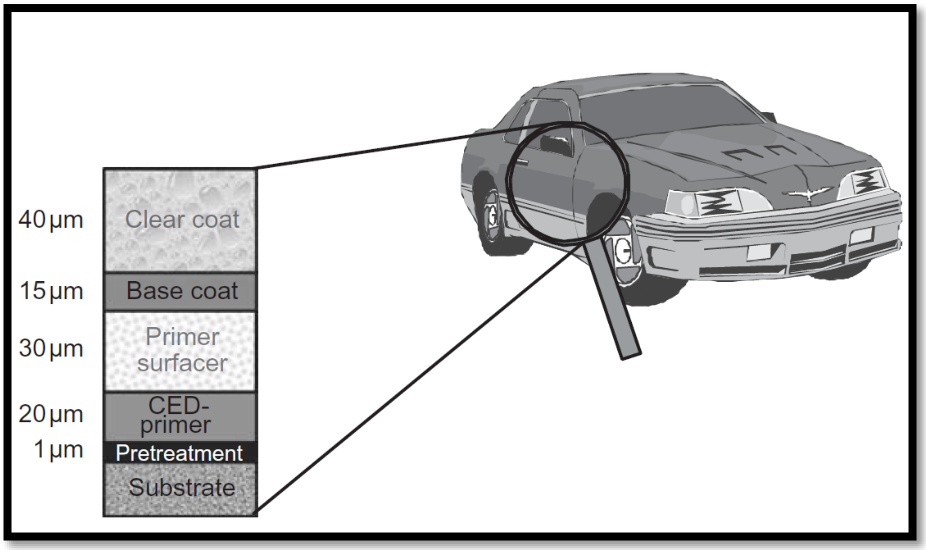

Fig. 3. Multilayer coating of cars [13].

The main components of the typical paints are [15-17]:

- **Pigments**: To give colour, opacity and usually to improve the resistance against the corrosion. The clear coat paint is the only one without pigment.

- **Additives**: To improve aspect, biological properties, conservation, transports, etc. and to prevent defects in the coating like bubbles, poor levelling or flocculation. Different additives are used depending on the requirements of the paints.
- **Binders or resins:** Provide adherence and resistance against mechanical and chemical strain. Amino resins derived from melamine are the most used resins in the automotive industry. These resins are made by a reaction between melamine, formaldehyde ($CH_2=O$) and alcohols (ROH).
- **Fluidising medium**. Depending on the chosen fluidising medium the paints could be waterborne or solvent borne. Additionally, there is another kind of paints based on a powder system but this is not commonly used in Europe. All of them contain different quantities of solvents in their composition. It is important to determine the operational conditions at the plant depending on the kind of paints used at each painting step.

1.4 Formaldehyde

Formaldehyde is a simple organic volatile compound, which chemical formula is H-CHO. All organic life forms produce formaldehyde that is emitted to the environment. Moreover, it has a wide range of applications so it is also manufactured industrially. In the last years, almost 9% of the total formaldehyde production in Europe was melamine Formaldehyde resins. These resins are fast-curing and can resist high temperatures and chemical damages so that, they are usually used in the composition of surface coatings of vehicles [18-20].

Through any vehicle manufacturing painting processes, formaldehyde can be released in two different ways. Firstly, a small percentage of free formaldehyde is present in the paints and therefore it can be emitted to the atmosphere through the exhaust air coming directly from the paint booths. And secondly, during the paint curing process at high temperatures the melamine-formaldehyde structure is broken, releasing formaldehyde which will be emitted to the atmosphere if no abatement equipment is installed or if the abatement system is not able to completely destroy the formaldehyde [14].

1.4.1 Formaldehyde emissions legislation.

The Regulation (EC) No 1272/2008 of the European Parliament and of the Council on classification, labelling and packaging of substances and mixtures [22] (CLP Regulation) has the main purpose to ensure a high level of protection of human health and the environment by harmonising the criteria for classification of substances and mixtures, and the rules on labelling and packaging for hazardous substances and mixtures. To reflect the adaptions to technical and scientific progress, this regulation needs to be constantly revised and corrected, thus the classification of chemicals is regularly updated and new substances can be reclassified as hazardous.

Besides, the Directive 2010/75/EU on industrial emissions [9] establishes the rules of integrated pollution prevention and control from industrial activities and is applicable to the industrial processes associated with vehicle assembly painting plants. This Directive sets emission limit values for carcinogens, mutagens, or substances toxic to reproduction. With one of the latest Adaptions to Technical Progress of the CLP Regulation in 2015 [8], formaldehyde has been reclassified to receive the Hazard Statements H350, *may cause cancer*, and H341, *suspected of causing genetic defects*. With this higher cancer-causing classification, the Industrial Emissions Directive is immediately applicable and compliance with the new applicable emission limit value for formaldehyde emissions must be guaranteed, forcing all European vehicle manufacturers to evaluate their legal situation and to implement technical and operational countermeasures to reduce or eliminate formaldehyde emissions.

2. GOAL AND SCOPE OF THE STUDY

2.1 Goal of the study

Due to the new formaldehyde classification, as it was explained before in this work, the company performed formaldehyde measurements in all its panting plants across Europe. Some modifications were implemented by the paint manufacturers in the paints composition that helped to reduce the formaldehyde emissions from the painting booths. Additionally, technical actions were already taken at the painting installation to reduce those emissions from the Primer coat process. Also, it is being studying different abatement technologies have been evaluated for its installation at the Top coat process to eliminate formaldehyde emissions. This project is based on the LCA of those improvements in order to analyse their environmental impacts comparing the results with the situation of the plant on2015.

The main goals of this project are:

- Detect the hot spots from the main painting processes that cause the highest environmental impacts.
- Propose possible future actions to reduce the impacts based on the hot spots identified.
- Study the environmental impacts of the different corrective actions that are already implemented at the plant to reduce the formaldehyde emissions as a single Scenario in order to be able to compare the environmental situation before and after those actions.
- Comparative study of the potential environmental impacts of the two possibilities that are being studied by the company to reduce the formaldehyde emissions at the Top coat ovens.
- Economic comparative study between the two different alternatives for abatement technologies. Discussion between the results and the real decision of the company.
- Study of another additional improvement Scenario. Future possible application.
- Comparative analysis of the different Scenarios of study from the direct emissions and human toxicity point of view to evaluate if the target of the Industrial Emissions Directive is achieved through those actions.

2.2. Scope of the study

2.2.1 Process description. Case of study

This work is focused on the three most important processes within the coating operations because they were identified as the most relevant from the formaldehyde emissions viewpoint. The indicated processes are electrodeposition (ELPO), Primer and Top coat. The detailed scheme of the material and energetic balance of the three important steps of the painting process taken into consideration in this study cannot be included on this public version due to the confidentiality agreement.

*__Working conditions of the plant cannot be shown in this public version due to the confidentiality agreement*__

2.2.2 Functional unit

The functional unit provides a reference to which the inputs and outputs are related [23-24]. The functional unit chosen was **1hour** of operation. Thus, all collected data and calculations are referred to one hour of operation in 2015.

2.2.3 System Boundaries

The system boundaries determine which unit process is going to be included within the LCA. The selection of the system boundary has to be done in accordance with the goal of the study [23-24].

The following scheme shows a summary of all painting processes. Those processes inside the red square are the ones included in the studied system.

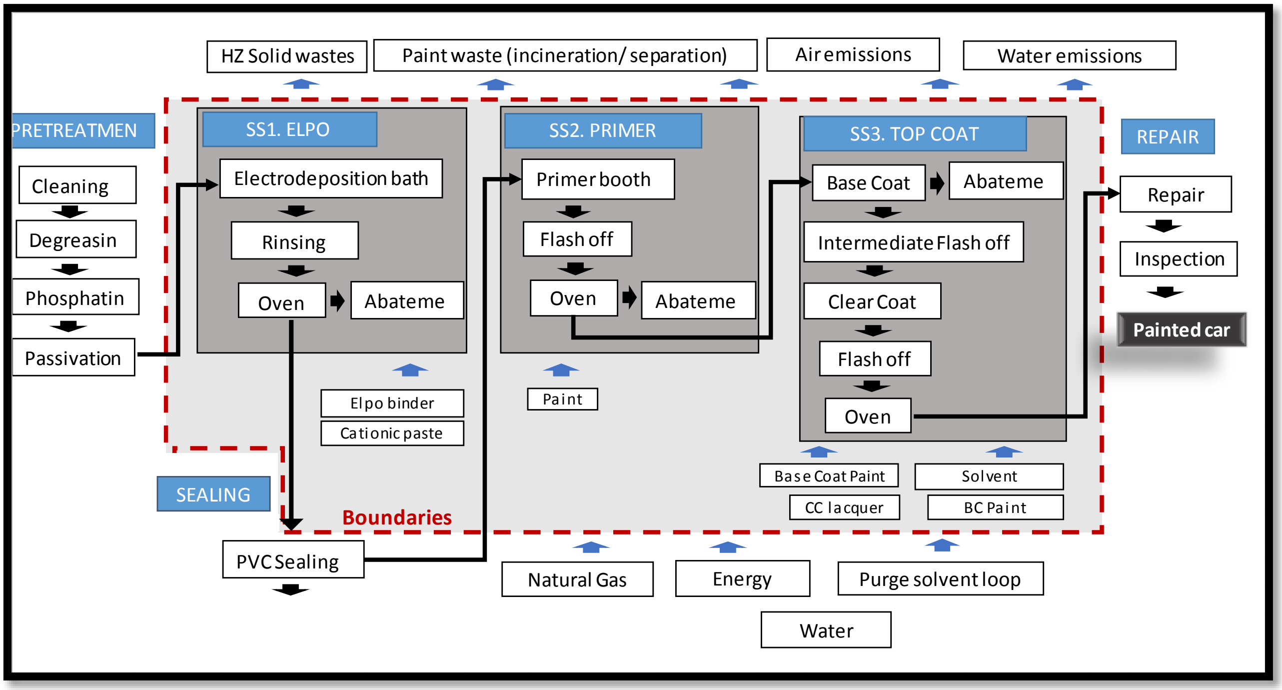

Fig. 4. Process summary and system boundary.

Assumptions made for the development of the project are strongly related with the working procedures of the plant, therefore cannot be shown in this public version due to the confidentiality agreement

3. DESCRIPTION OF IMPROVEMENT SCENARIOS

In order to analyse the environmental impact of the vehicle painting process under different improvement modifications that were introduced or are currently being implemented at the studied painting plant, different Scenarios were studied.

3.1 Chronology

The next figure shows the implementation timeline of the different Scenarios studied in this project for the plant of study.

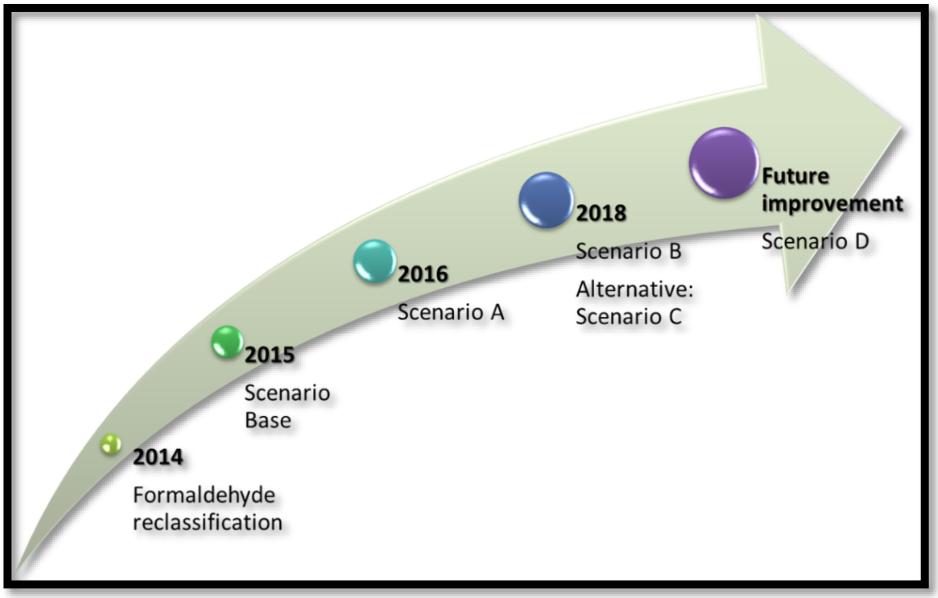

Fig. 5. Timeline of the different improvement Scenarios to comply with new emission limits.

The starting Scenario was defined as “Basic case” and represents the painting plant as it was operated in 2015 when the first measurements were performed.

In 2016, the first set of corrective actions was implemented and it was included in the first studied Scenario, “Scenario A”. This consists of a reduction of the amount of free formaldehyde in the paints carried out by paint manufacturers and a decrease of the emissions from the Primer coat process by introducing technical and operating improvements. After that, the company efforts were focused on reducing the emissions from the Top coat process. For that, the company is currently installing a regenerative thermal oxidiser for the exhaust air of the Top coat ovens projected to be finished in 2018. This was analysed as “Scenario B”. This comparison was made to determine which of both alternative Scenarios would have less environmental impact. Furthermore, a possible future improvement Scenario was analysed as “Scenario D”.

It is important to bear in mind that only the environmental impacts caused by the painting process working under these new modifications were analysed and not the impact of the implementation itself.

3.2 Scenario A

The first Scenario includes different corrective actions already implemented at the plant.

Because of the new hazardous classification of formaldehyde, the paint manufacturers improved their production process to reduce the amounts of free formaldehyde in their paints. In this Scenario, Primer and Top coat paints have reduced amounts of free formaldehyde in its composition.

The emissions from the flash off area were redirected to the oven to be treated commonly.

It was increase the temperature of the incinerators at the Primer ovens in order to improve their abatement capacity.* **Detailed explanation of this implementation is not shown in order to protect the confidentiality of the company***

The next chart shows the trend line of CO, total carbon and NOx emissions in relation with the temperature of the incinerator.

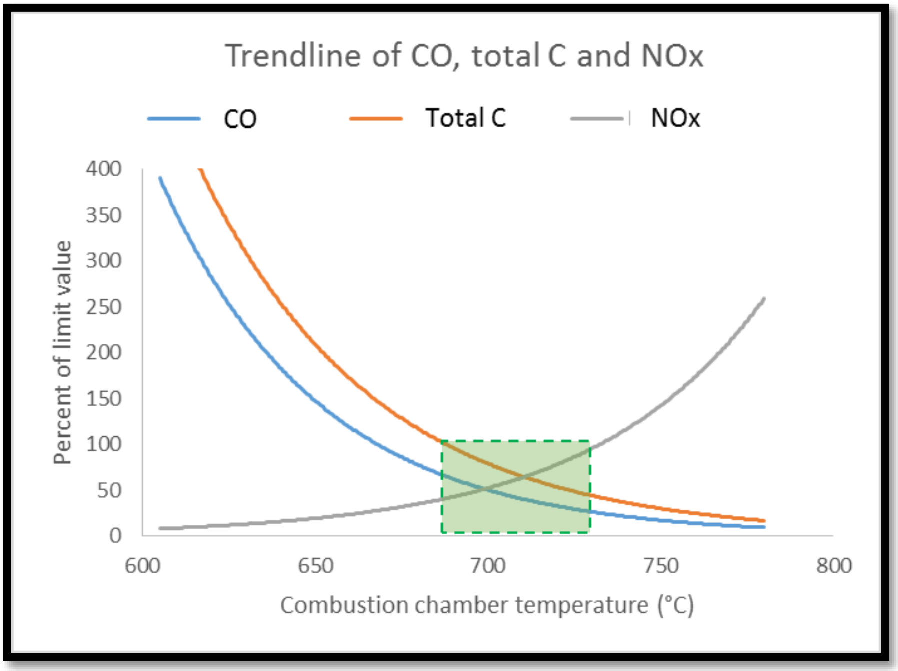

Fig.6. Trend line of CO, total carbon and NOx according to the temperature of incineration inside the abatement installation. Adapted data from VDI [14].

CO and total carbon follow the same trend, that is, the higher the temperature, the lower the amount emitted of these pollutants. However, NOx has the opposite behaviour, it increases with the temperature. It is necessary to achieve an equilibrium to have the lowest concentrations possible of all pollutants. The green square shows the most ideal situation, where the amounts of all parameters, CO, C total and NOx, remain in their lowest values, so the ideal working temperature has to be within this range.

3.3 Improvement Scenario B and C

To decrease formaldehyde levels at the Top coat ovens, the option selected by the company was the addition of abatement systems at this oven.

The abatement equipment commonly used at vehicle painting plants is a thermal oxidiser. Oxidisers can recycle the 95% of the heat excess and use 20 times less heat requirement for the burner than other kind of abatement. There are two different oxidisers used by the vehicle manufacturing companies: Regenerative (RTO) and Recuperative (TAR) Thermal Oxidisers [14, 25].

Although the company already decided to install RTO abatement system at the plant to reduce the emissions at Top coat ovens, this project reflects a comparison between these two alternatives from the environmental impact and economical point of view.

Calculations were made by the company to estimate the number of systems for each oxidiser studied needed to ensure the required treatment of the emissions. Also, an evaluation of the energy demanded for each type was made by the company.

3.3.1 Improvement Scenario B

A Regenerative Thermal Oxidiser (RTO) is a regenerative pot-combustion emission control system that uses a flame to oxidise the organic compounds at optimal temperatures around 800-850°C. The raw gas enters to the system and is heated by a ceramic that covers the device. This raw gas is burned and the final clean gas is cooled using a mixed-bed as a heat exchange. The heat is stored at the ceramic materials allowing to reuse it to heat the incoming raw gas, which reduces the amount of fuel needed. The destruction efficiency of this kind of abatement is between the 95-98%. This system is independent to the whole painting process, meaning, if the abatement malfunction suffers any malfunction, it is not necessary to stop the production [14].

The next figure explains the different parts of a common Regenerative Thermal Oxidiser.

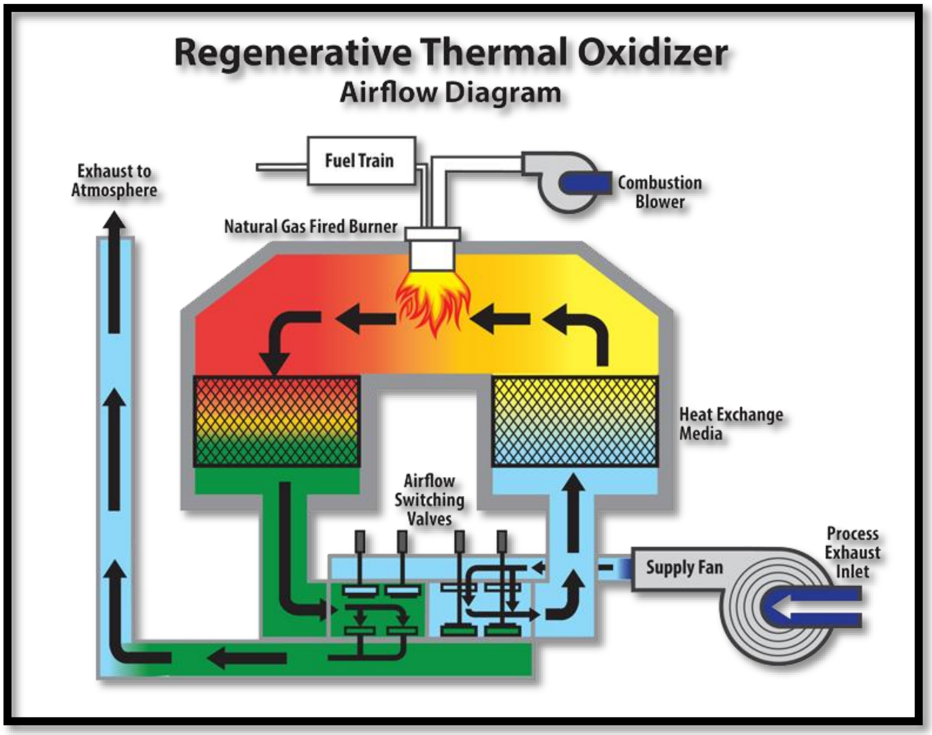

Fig. 7. RTO abatement scheme [26].

This Scenario is based on the addition of a regenerative thermal oxidiser abatement system at the Top coat oven. RTO energy is supplied by several burners using Natural Gas as fuel.

3.3.2 Improvement Scenario C

Recuperative Thermal Oxidisers (TAR) or incinerator has a combustion chamber working at optimal temperature of 700-740°C. There is a flame within the system that incinerates the organic compounds through to an almost complete oxidation. It contains an integrated heat exchanger to preheat the raw gases. It is usually integrated in the system, so that if the incinerator has to be turned off, the whole process has to be stopped [14].

At the following figure there is a summary of the different parts of a common Recuperative Thermal Oxidiser.

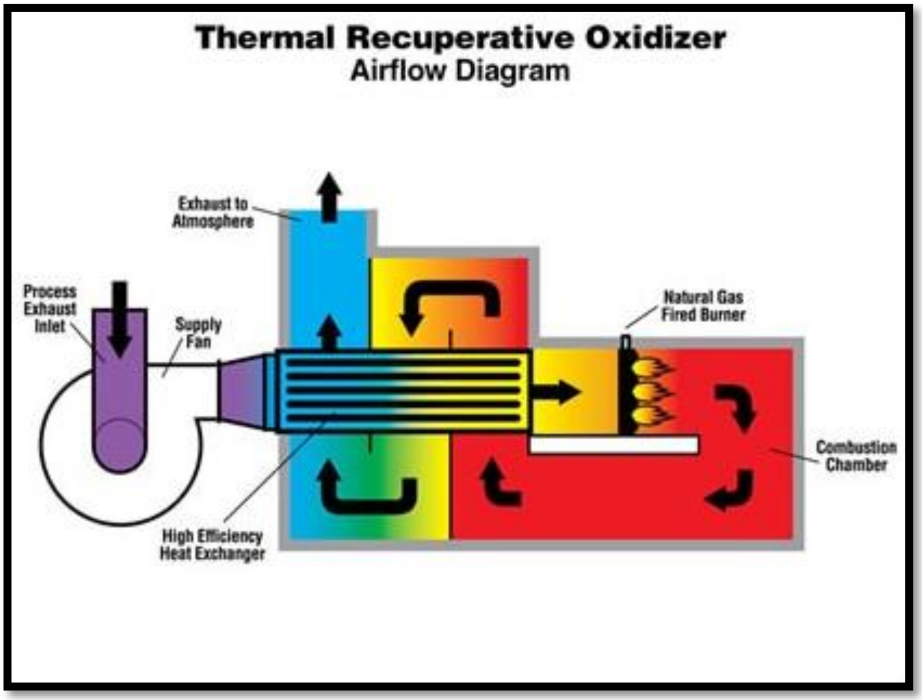

Fig. 8. TAR abatement scheme [26].

Scenario C contemplates the addition of TAR abatement systems at the Top coat final ovens. The enthalpy of the clean gases is used to heat the ovens in the process saving energy to the plant so that the burners currently installed to heat the ovens would be stopped or removed.

3.4 Improvement Scenario D

In addition to the installation of an abatement system for the Top coat oven exhaust air, other future improvements were analysed to reduce VOC emissions to lower levels

In Scenario D, the painting process with a complete treatment of the emissions from the Base coat spray booths was simulated. This Scenario was simulated over the data from the Scenario B because of the company decision of installing an RTO at the Top coat ovens**.* Information about the current situation of the plant has been deleted due the confidentiality agreement***

4. METHODOLOGY

LCA is a technique to determine the environment aspects and potential impacts related to a product or activity. The International Organization for Standardization (ISO) provides guidelines for conducting an LCA within the series ISO 14040 and 14044 [23-24]. In this project, a LCA from a gate to gate perspective was performed to analyse the potential environmental impact from the vehicle painting process. In this 'gate-to-gate' approach only inputs of materials, energy, natural gas, and outputs (e.g. emissions, waste) associated with the processes within the boundary were included. Upstream and downstream activities as other steps from the vehicle manufacturing, distribution and use were not part of this study.

The commercial LCA software used in this project was **SimaPro V8.2**. A previous collection of a detailed inventory with all inputs and outputs of the system is necessary to be able to enter it in the program and to obtain the environmental impacts associated with each component of the studied system. The collection and development of the inventory is explained in the Chapter 5. To introduce these data at the system, database **Ecoinvent 3.0** was used.

4.1 Impact assessment.

Impact assessment is a technical, quantitative and qualitative process to characterise and measure the effects of the environmental burdens identified in the inventory. This approach allows the identification of the potential impacts of different impact categories, characterisation, and potential damage for safeguard subjects such human health.

The selected method for the impact assessment on the SimaPro software was **Recipe midpoint V1.12.** This method has a scientific solidity, it is easy to use and interpret and it is internationally accepted. This method focuses on the environmental impact and damage. It distinguishes 18 impact categories [27-30].

- Climatic change (CC) (kg CO_2 eq): Impact related to the average increase of temperature of the terrestrial atmosphere and of the oceans observed in the last decades. The midpoint level uses the latest (2007) IPCC equivalency factors for three time horizons (20, 100 and 500 years).

- Ozone layer depletion (OD) (kg CFC-11 eq): It measures the negative effects on the ability to protect against ultraviolet radiation from the atmospheric ozone layer. Based on time-explicit forecast of demographic developments up to 2100.

- Terrestrial acidification (TA) (kg SO_2 eq): Linked to Ecosystem damage and time horizon dependent. It analyses the decrease on the neutralising capacity of soil.

- Fresh water eutrophication (FT) (kg P eq) and Marine eutrophication (MT)(kg N eq): Excessive growth of the algae population due to the artificial enrichment of river, reservoir or marine waters as a result of the massive use of fertilisers and detergents.

- Human toxicity (HT) (kg 1.4-DB eq): It considers the harmful effects on human health due to the absorption of toxic substances through inhalation of air, food or water intake, or penetration through the skin.

- Photochemical oxidant formation (POF) (kg NMVOC): Photochemical pollution occurs due to the presence of oxidants, caused by the reaction of nitrogen oxides, hydrocarbons and oxygen with ultraviolet radiation from the sun. It is the principal responsible of tropospheric ozone which is hazardous for the human health.

- Particular matter formation (PMF) (kg PM10 eq). Particles and inorganic substances with respiratory effects. It measures the harmful effects on human health due to particulate emissions and their precursors (NOx, SOx, and NH_3).

- Terrestrial ecotoxicity (TET), Fresh water ecotoxicity (FET) and Marine ecotoxicity (MET) (kg 1.4-DB eq): Ecotoxicity is the result of a number of different toxicological mechanisms caused by the release of substances with a direct effect on the health of the ecosystem. These categories of environmental impact are related to the toxic impacts that affect to terrestrial, fresh water or marine ecosystems, that are harmful to different species and that change the structure and function of the ecosystem.

- Ionising radiation (IR) (kBq U235 eq): Related to the damage to Human Health due to the radioactive material emissions to the environment.

- Agricultural Land Occupation (ALO) and Urban Land Occupation (ULO) (m^2a): Category of impact related to the use (occupation) and conversion (transformation) of an area of land by agricultural or urban activities.
- Water depletion (WD) (m^3), Metal depletion (MD) (kg Fe eq) and Fossil depletion (FD) (kg oil eq): Related to the consumption of material extracted directly from the environment.

4.1.1 Characterisation

ISO 14040 on Lifecycle Assessment determines the characterisation as mandatory. The impact of each emission or resource consumption is modelled quantitatively, according to the environmental mechanism. The representation of the characterisation of the impacts is given in some charts. In these charts, each component of the system is represented by a percentage taking into account their contribution to the whole environmental impact over that category [23-24, 27-30].

In this project, the characterisation of all impacts was analysed to obtain the hot spots of the system, i.e. the contributions that cause the highest environmental impact.

4.1.2 Normalisation

Although ISO 14040 does not mark the normalisation as mandatory, it is a useful tool to compare the environmental impact from the different contributions of the system of the different Scenarios.

The result of the characterisation is adjusted applying a score, the so-called characterisation factors, with the aim at expressing in a common unit all contributions within the impact category. The characterisation factor or scores are associated with a common reference that allows the comparison between different impact categories [23-24, 27-30].

To represent the normalisation data, the index represented has no units and it is only useful to determine which impact is the most relevant within the analysed system. The scale in this case is not relevant and it can vary depending on the studied impact or the method used.

5. LIFE CYCLE INVENTORY

Life Cycle Inventory (LCI) is a compilation and quantification of input and output data with regard to the system being studied. The outcome of the LCI catalogues the flows crossing the system boundary and provides the starting point for life cycle impact [23-24].

5.1 System definition and Data quality

The following scheme shows the different steps that have been followed for the development of this project. The green part explains the system definition, i.e. the basic bibliographic information and technical facts required to understand the company, the painting process and the problem of study. In the blue part the data quality process is shown.

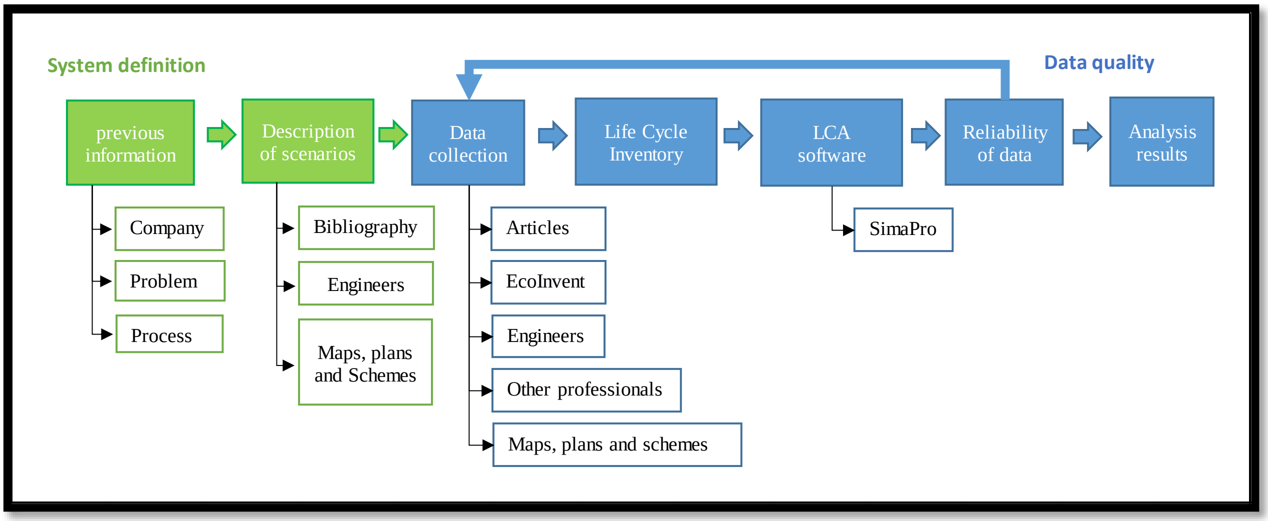

Fig. 9. System definition and data quality.

After all the previous information was collected, a qualification of all the inputs and outputs was made by schemes and material and energetic balances. After that, the quantification of those data was developed by the inventory.

During the elaboration of the inventory several types of sources were consulted in order to have reliable and accurate data.

After that, all inventory data were transferred to the chosen software to analyse the environmental impacts affected for the different processes. It is important to bear in mind that some iterations with the software were needed in order to achieve the highest accuracy as possible. When the hot spots are detected, it is necessary to ensure that the source of the related data is reliable enough to obtain results as solid and certain as possible.

5.2 Types and sources of data

Data selected for an LCA depends on the goal and scope of the study. For the development of this project, most of the data were collected from the production site associated with the unit within the system boundary. Besides, other data from alternative sources as books or papers, other similar plants, internal communications or additional information were needed in order to complete all the required information to elaborate the processes´ inventories. All data collected in this project include a combination of measured, calculated and estimated data. In this chapter, all data inventories are shown indicating the source of each figure and, when required, how it was calculated.

Data were classified according to their level of reliability.

1. Data from the plant. As far as possible, real data from the studied plant were used. Different reports with relevant information were checked, as well as reports with real air emissions measurements made at the plant. The location of the studied plant is Europe and all the data compiled for the inventories of the base case Scenario were from 2015.

2. VOC and material balances from the plant. To determine the VOC emissions and the materials used at the plant, data were taken from the VOC emission balance report that the plant engineers had developed with real data from 2015 and 2016.

3. Safety Data Sheets from the materials (REACH) and other information from the material´s suppliers. This information came from external companies.

4. Calculations based on data given by the plant. Assumptions and calculations were made to have a good allocation of some data using information of the material and energy consumption.

5. Internal communications. To understand the whole system, several meetings were needed with different engineers and experts on the paints used at the plant, the processes and water and energy management. Despite of these data not being reflected in any report from the plant, the information from this source was considered reliable enough to be taken for the purpose of this project.
6. Data from a different plant of the same company with similar processes and characteristics. Some data were not available from the studied plant, therefore reports from other similar plants of the company were taken.
7. Bibliographic information. Books, papers, legislation and BREF reports were reviewed to understand the common vehicle painting processes and to verify and allocate the data to the studied processes.
8. Other calculations. It is referred to estimations made through different sources or following simple mathematical rules.

Most of the data were compared with different sources to ensure its veracity, especially when those data were obtained as a percentage or an interval value.

5.3 Inventory

As it was mentioned previously, the functional unit chosen was 1 hour of operation. According to that, all the data exposed below are referred to that unit. It was needed to calculate the production hours during a year in order to have all the data in the same units. This calculation was made through the assembly production calendar of 2015 given by the plant.

The detailed inventories of inputs and outputs following explained define the initial situation of the plant as it was working in 2015. This Scenario was called in this project “Base case”. For the analysis of the different Scenarios, modifications in the natural gas consumption, paint composition and in the air emissions were needed.

***This project was elaborated under a strict confidentiality agreement. Because of that, the inventories used for each process are not available in this public version*.**

5.3.1 Inventory for Scenarios

To analyse the impact of the different studied Scenarios, several modifications in the inventories were required.

***The table that compiles those changes has been delated due to the confidentiality agreement*.**

The following changes were made on the different Scenarios:

- **Paints.** Scenario A contemplates a change on the composition of all the paints used at the plant. The amount of free formaldehyde in the paints was reduced to a value below 0.1% so the suppliers do not need to label their products as carcinogenic as CLP Regulation reclaims. It was not possible to obtain the real amount of free formaldehyde that is currently present in the paints. Thus, the higher amount possible was assumed, i.e. 0.099%. This new paints´ composition remains in all the different Scenarios.
- **Natural Gas variation.** The variation of the natural gas for the different Scenarios were calculated following some information from the engineers of the plant.
- **VOC and formaldehyde emissions** were estimated or calculated by VOC mass balance simulating the different characteristics for each one.
- **NOx and CO.** For the improvement Scenarios that are not implemented at the plant yet, air emissions data related to the abatement installations (NOx and CO) were not available. Data from other plants with similar characteristics were taken and adapted to the studied plant.
- **Economic analysis.** Additionally, for Scenarios B and C, where two different abatement systems for the Top coat ovens were proposed, an economic analysis was made. For that, was taken into account the lifetime of both abatements, costs of maintenance and installation and natural gas consumption. The prevision of the cost due to the natural gas consumption through the lifetime of the abatement alternatives was performed using the IPC data from the last ten years [34] and the current natural gas cost [35].

6. RESULTS

This chapter includes the Life Cycle Impact assessment and interpretation. The assessment is the phase of the LCA that involves the evaluation of the magnitude and significance of the potential environmental impacts for the system. The interpretation is the evaluation of the results related to the goals and scope of the project to reach conclusions and recommendations [23-24].

Once all data were collected in the inventories described in chapter 5 and inserted in the SimaPro software, results were obtained and analysed. This chapter is structured following the goals described in chapter 2.

6.1 Painting process base case analysis

Firstly, the global system was analysed to understand which process contributes with the higher environmental impact to the whole system. Next chart shows the characterisation obtained from the data of the whole process in 2015, when the concerns about formaldehyde emission levels started and the first measurements took place. The components taken into account for this chart were the three subsystems from ELPO, Primer and Top coat processes and all inputs and outputs that could not be allocated to the different processes.

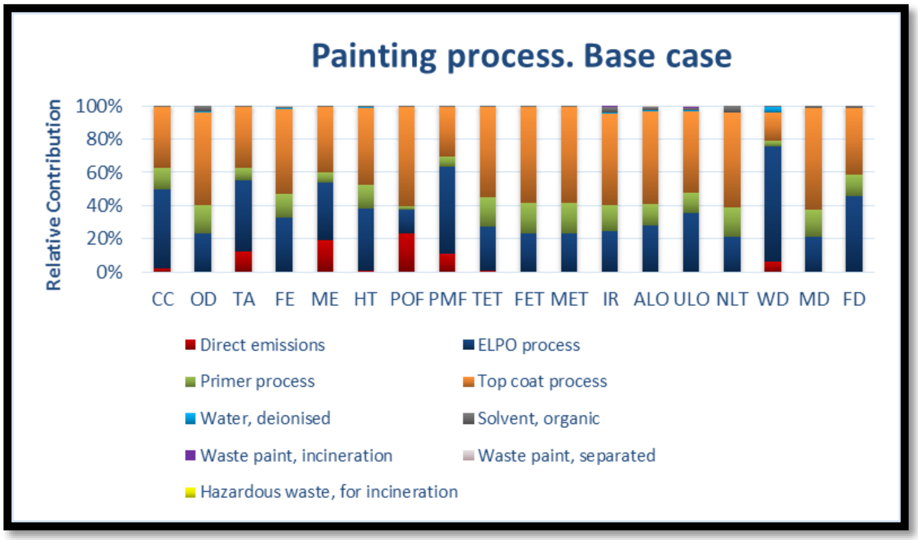

Fig. 10. Characterisation of the system "Painting process base case".

Top coat is the largest process with the highest material consumption and emissions. Therefore, as it was expected, it can be seen in the chart that Top coat process has the highest contribution to the environmental impact for most of the categories of impact.

However, it has to be taken into account that the **ELPO process** plays an important role in all the impact categories being the highest contribution in the categories of climatic exchange (CC), terrestrial acidification (TA), particular matter formation (PMF), water depletion and fossil depletion (FD) essentially because of the materials used in this process.

In the following subchapters, the results from the analysis of each process are shown in detail to determine the components that constitute the potential cause for the impacts. Some actions were also proposed to be studied and implemented in the future to decrease those impacts following the indications from the STS BREF.

6.1.1 ELPO process

The first subsystem within the boundaries of the system is the ELPO process.

The figure below represents the characterisation of this process obtained through the software using the inventory data explained in chapter 5.

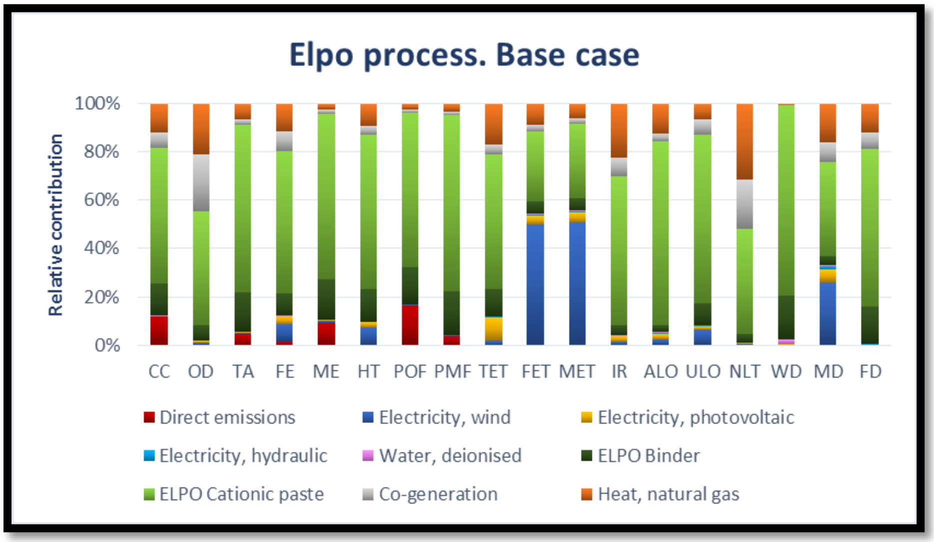

Fig.11. Characterisation of the subsystem (SS1) "ELPO process base case".

The **ELPO cationic paste** has the most important contribution to the total environmental impact from this process. ELPO cationic paste and binder were not found in the Ecoinvent database on the software. Therefore, those materials were also introduced as a subsystem inside the ELPO process. For that, the composition of the materials was analysed. Due to the high impact related to ELPO cationic paste in most of the impact categories, its characterisation was carried out. In this characterisation, it was observed that the use of **epoxy resins** on its composition is the main cause of the impact essentially because of the CO_2 emissions during its production. According to this result, a future recommendation is the research and development of different resins that can be used for the production of ELPO materials with a lower environmental impact by the paint producers, or a modification in their production process leading to a reduction in the CO_2 emissions.

It is also important to highlight the high contribution on freshwater and marine ecotoxicity of **the wind energy**. Data for wind electricity was taken from the Ecoinvent using the "*Electricity, high voltage {ES}| electricity production, wind, >3MW turbine, onshore | Alloc Def, U"* parameter after being checked that this is the most suitable to the case of study. Analysing the data and the characterisation of this type of energy, it was concluded that this ecotoxicity character is a consequence of the use of copper on the construction of the wind turbines. Copper is a heavy metal that affects essentially the water ecosystems. We can find those unusual values from the wind energy in each of the processes. The supplier of the energy for the plant is an external company and it is not related exclusively with vehicle manufacturers. For this reason, an improvement to the plant in order to reduce these impacts cannot be suggested.

With regard to the direct emissions from this process, the results indicate that they are not relevant in any of the impact categories. For this reason, the following improvement Scenarios studied at this project are not affecting this process.

6.1.2 Primer process

After ELPO process, the following step studied at the painting plant was the Primer process. The results of the characterisation of this process are shown in the next chart.

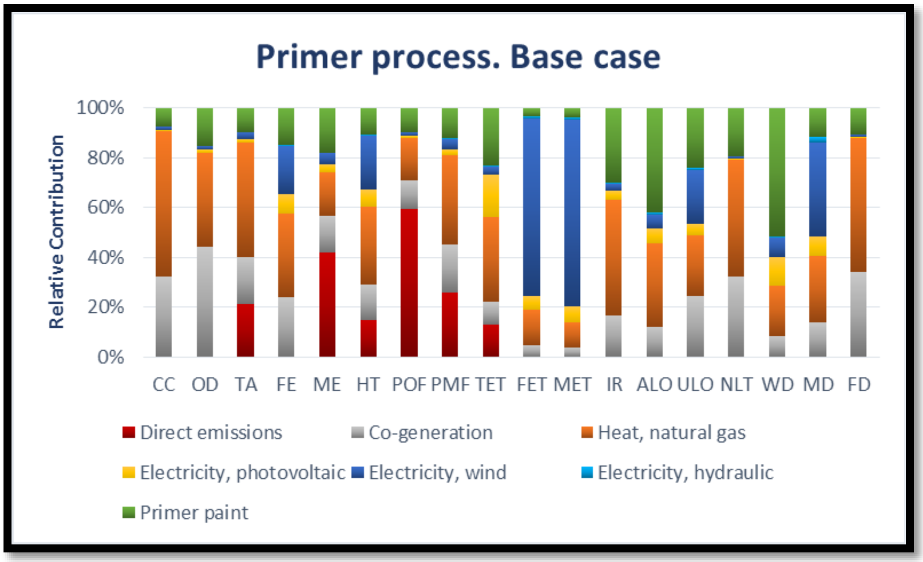

Fig. 12. Characterisation of the subsystem (SS2) "Primer process base case".

Most of the impact categories are highly affected by the natural gas consumption. This impact is associated with its extraction and use. Currently, there is no feasible alternative to the natural gas used as a fuel to feed the burners for the abatement equipment, so that the impact related to that cannot be reduced.

The percentage of the renewable energy from each process was taken from the Spanish electrical mix, so that percentage is the same on all processes studied on this project. As it was observed for the ELPO process, **wind electricity** represents a high contribution to the impact in certain categories.

In this process, the **direct emissions** have the main contribution to the marine eutrophication and photochemical oxidant formation impacts due to the NOx emissions. Although the direct emissions are not the principal cause of the toxicity categories, it also plays an important role on them. The first Scenario studied in the section 6.2 contemplates an improvement on this process in order to reduce the air emissions and, as a consequence, the impact related to human toxicity.

6.1.3 Top coat process

Finally, the last painting step was analysed. Top coat includes Base coat and clear coat processes, being one of the most complex within the system. As in the previous processes, the results of the characterisation of this step are shown in the graph below.

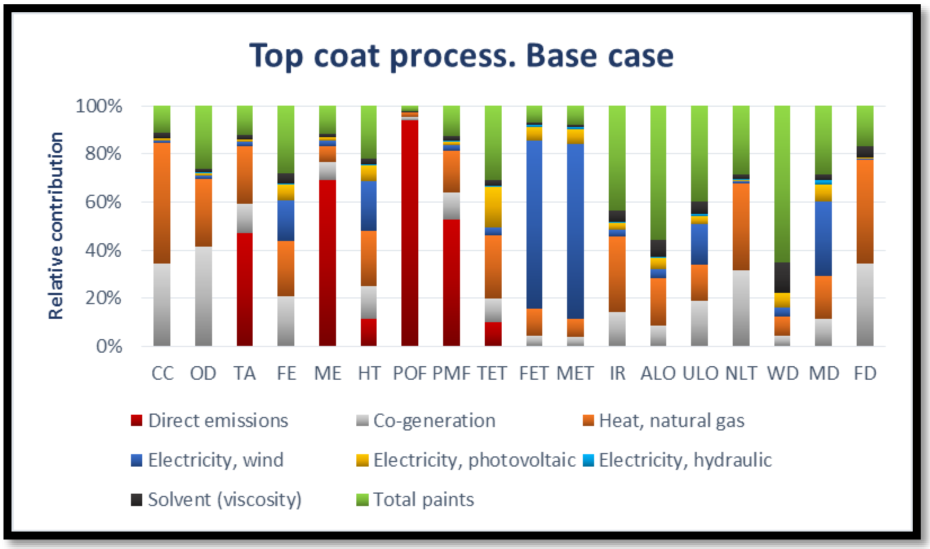

Fig.13. Characterisation of the subsystem (SS3) "Top coat process base case".

To analyse this process, the elaboration of three subsystems for the paints was needed. These subsystems were "Base coat paint", "white paint" and "clear coat lacquer". However, to make the chart more visual, the impact of these three paints was analysed together as "**Total paints**". As it was observed on the characterisation of the paints on ELPO process, the three different paints used at Top coat have high levels of **epoxy resin** on their composition which is the main cause of the impact related to the paints.

Marine eutrophication, terrestrial acidification, photochemical oxidant formation and particular matter formation impact categories are the most affected by the **direct emissions**. Almost the whole photochemical oxidant formation impact is due to direct emissions, mainly because of the NOx emissions at the exit of the incinerators.

As in Primer process, direct emissions are not the main cause of the human toxicity, nevertheless as a consequence of the new classification of formaldehyde, the Scenarios B, C and D studied different technical improvements to reduce the formaldehyde emissions and therefore the human toxicity.

6.2 Scenario A. Current situation

As explained in previous chapters, Scenario A considers the current situation of the paining plant after the implementation of the following modifications:

- Less formaldehyde in all the paints (Primer, Base coat and clear coat). In 2015 the amount of formaldehyde at the paints was around 0.3% as average and nowadays it contains less than 0.1%.
- Increase of the temperature at the Primer incinerators.
- Redirection of the flash off emissions to the Primer oven.

The change on the paints´ composition made by the paint producers slightly decreases all impact categories at Top coat process, being the highest decrease in urban land occupation decreasing the impact by 0.04%. The main reason of this change on the composition was the new formaldehyde classification, therefore human toxicity was separately analysed. Human toxicity at Top coat decreases its impact by only 0.025%.

This Scenario is fundamentally focused on the reduction of the formaldehyde emissions at Primer process with the aim at reducing the impact at the toxicity categories. Increasing the temperature at the incinerators involves an important increase of the natural gas consumption.

As a consequence of the higher natural gas consumption, all impact categories dramatically increase its impact. However, as it can be observed in the next chart, human toxicity decreases its impact considerably which was the target of the implemented actions included in Scenario A.

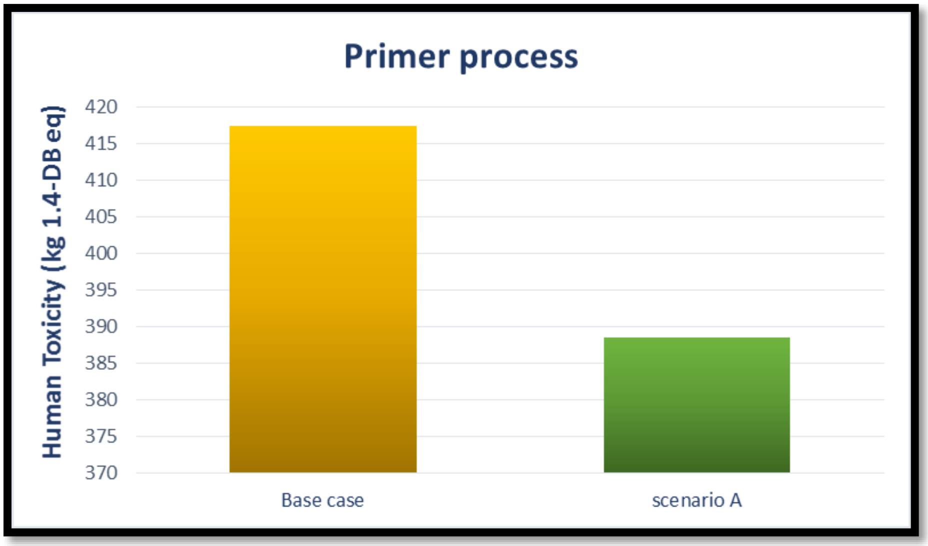

Fig.14. Human toxicity Characterisation comparison between both Scenarios.

The graph shows a comparison between the results of the characterisation for the **Human toxicity** category between both Scenarios. Human toxicity impact was reduced by 7% with the implemented actions included in Scenario A. Besides, terrestrial ecotoxicity impact is decreased by 4% with these countermeasures.

6.3 Improvement Scenarios at Top coat ovens. Scenarios B and C

In this section, a comparison between the two different abatement technologies that were studied by the company to be implemented for the Top coat process was performed.

As it was explained before, the company is currently installing an RTO at Top coat process to treat the air emissions from the ovens. This implementation is projected to be finished in 2018. In this work, this improvement was studied under Scenario B. Nevertheless, another alternative of abatement was also analysed. Scenario C reflects the installation of several TAR instead of an RTO at the Top coat ovens. One of the main advantages of this Scenario is that the total natural gas consumption is reduced because the heating excess can be used to heat the ovens, and therefore the burners for the ovens are no longer necessary.

Next Table collects the reduction or increase on the different environmental impact categories percentage related to the Scenario A for the Top coat process.

Table 1. Percentages of variation for each impact for the Scenarios B and C with respect to the current situation of the plant (Scenario A) impact at Top coat process.

	% Variation Characterised Index	
Impact category	**Scenario B**	**Scenario C**
CC	🔴 8.8%	🟢 -8.1%
OD	🔴 5.0%	🟢 -4.6%
TA	🔴 34%	🔴 25%
FE	🔴 4.1%	🟢 -3.8%
ME	🔴 44%	🔴 42%
HT	🟢 -3.3%	🟢 -11%
POF	🟢 -2.6%	🟢 -3.2%
PMF	🔴 36%	🔴 30%
TET	🟢 -2.0%	🟢 -11%
FET	🔴 2.0%	🟢 -1.8%
MET	🔴 1.4%	🟢 -1.3%
IR	🔴 5.6%	🟢 -5.1%
ALO	🔴 3.5%	🟢 -3.2%
ULO	🔴 2.7%	🟢 -2.4%
NLT	🔴 6.4%	🟢 -5.9%
MD	🔴 1.4%	🟢 -1.3%
FD	🔴 3.1%	🟢 -2.8%

In the table, categories that increase their impact in comparison with the Scenario A were marked with a red point. The green point represents the categories that were reduced due to the implementation of the two Scenarios.

If the normalised index for the impacts is analysed at Top coat process, it can be observed an increase on the **total impact by 4% under Scenario B**. On the other hand, Scenario C contemplates energy recovery, so that the Natural gas consumption is reduced. As a consequence of that, Scenario C shows a more environmental sustainable Scenario and most of the impact categories are reduced under this condition. This Scenario incomes a **reduction on the total normalised index around 2%.**

The target of building a new abatement installation for the Top coat ovens, TAR or RTO, is the reduction of VOC emissions, and essentially formaldehyde, therefore a reduction on the Human toxicity impact category is expected as it can be observed in the table 1 and in the next graph.

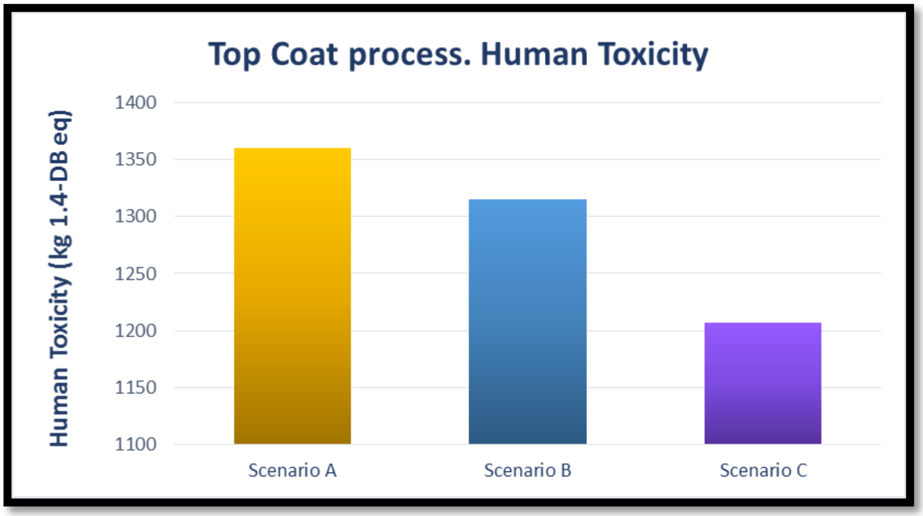

Fig.15. Comparison of Scenarios B and C versus the Base case from the human toxicity point of view. Characterisation.

In both Scenarios human toxicity is reduced considerably. Scenario B achieves a reduction of 3% with regard to the current situation while in Scenario C the percentage of reduction is 11%. However, as it was mentioned before, the company have decided to implement the Scenario B, i.e. the installation of an RTO at the Top coat ovens. To make this decision, the company took into account the economical factor and the implementation timeframe, which was significantly shorter. Because of that, in the following section both Scenarios were analysed from the environmental and economical point of view. This analysis was performed following two different criteria to select the studied environmental impact categories.

6.3.1 Economical analysis

To understand the company´s decision to install an RTO, an economic analysis was done. In order to do that, it was necessary to compile information about the costs for both abatement options and adjust them to the unit system taking into account the lifetime of each one. ***These data are confidential, so that it cannot be publicised at this public version***

This analysis was made following the example of the ISO 14045 related to Eco-efficiency [33]. Eco-efficiency assessment is a quantitative management tool which enables the study of life-cycle environmental impacts of the different Scenarios studied with its economic value. Two different criteria were taken into account for this analysis.

- Criterion 1: All the impacts affected by formaldehyde emissions.

Pursuing the target of the company, i.e. Formaldehyde emissions reduction, the normalised index of those impact categories related to this compound was analysed taking into account the economic factor. Formaldehyde affects human toxicity, photochemical oxidant formation and terrestrial, freshwater and marine ecotoxicity impact categories.

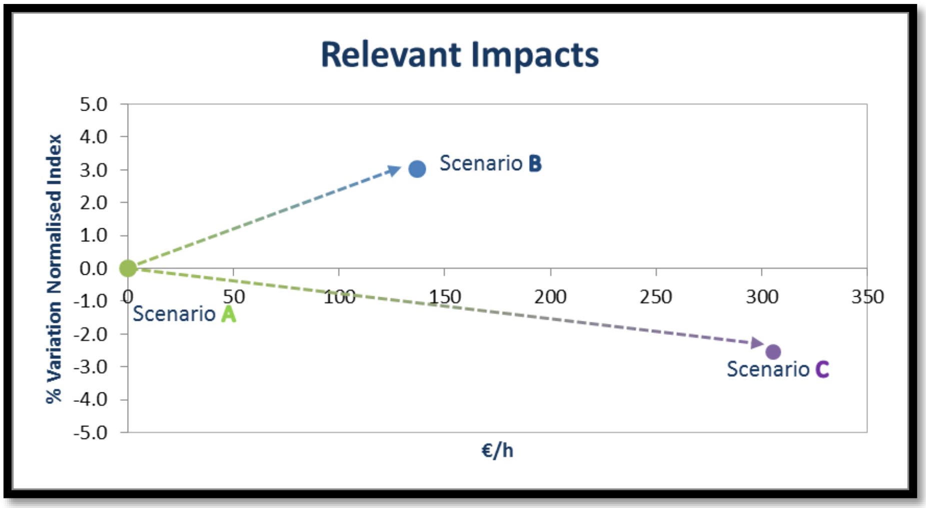

Fig.16. Eco-efficiency analysis. Scenarios B and C Versus Scenario A taken into account the impacts directly related to formaldehyde emissions.

Scenario A was taken as point of reference. Comparing both Scenarios, Scenario C is more expensive than B although in this case the impact is being reduced and with the Scenario B is slightly increased.

- Criterion 2: Human toxicity point of view.

The new hazardous classification of Formaldehyde had as overall purpose the reduction of damages on human health. Therefore, for the last criterion used to analyse the data, the normalised impact of Human toxicity was used.

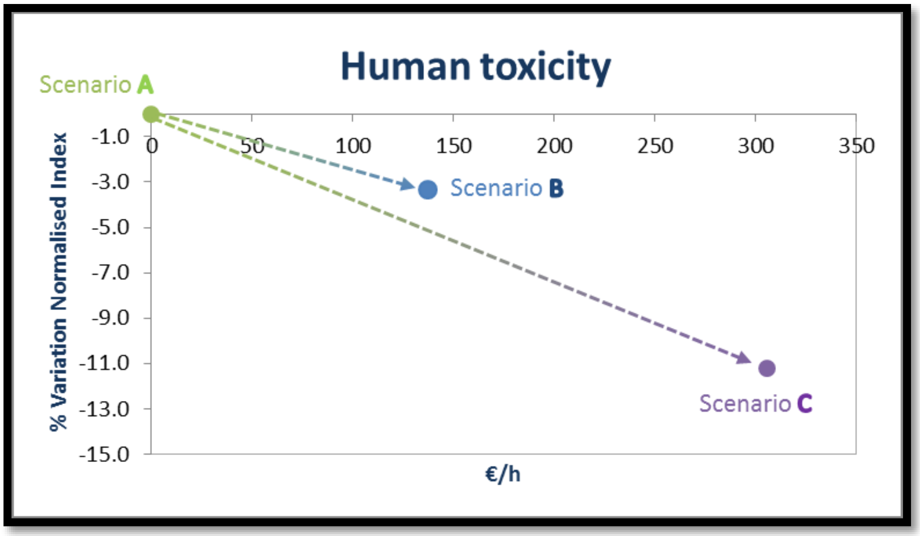

Fig.17. Eco-efficiency analysis. Scenarios B and C Versus Scenario A from the human toxicity impact point of view.

In this case, both Scenarios imply a decrease on the normalised index in relation to the current situation of the plant. As it was observed for the criterion analysed before, Scenario C is more expensive than B.

As it can be seen in the picture, the objective of the new classification could be achieved by both Scenarios. In the decision-making process, the economic aspect was more relevant for the company to finally decide the installation of an RTO at the Top coat ovens (Scenario B).

6.4 Scenario D. Future improvement Scenario

The last improvement Scenario is based on Scenario B. As the company decision was the installation of an RTO, Scenario D considers the RTO case and the complete capacity use of the Base coat booth abatement equipment installed to reduce the VOC emissions. This Scenario entails a considerable natural gas consumption increase. As it was concluded in the previous analysis, this means an increase on most of the impact categories.

The impacts from Top coat process from Scenarios B and D were compared in order to determine if this future action would improve the situation of the process once the RTO is operating.

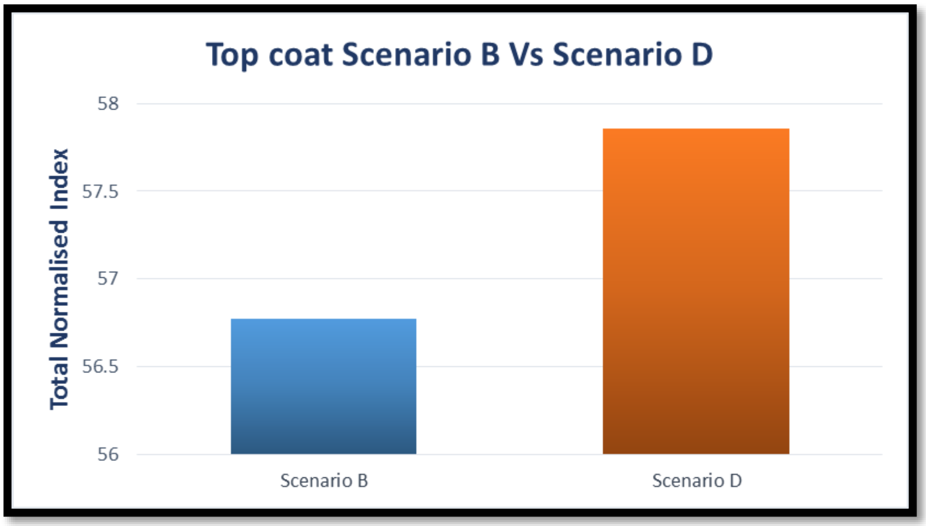

Fig. 18. Total normalisation results. Comparison between the Scenarios B and D.

The chart shows the results of the comparison of the normalisation index obtained analysing the total from all the impact categories of both Scenarios.

Although the photochemical oxidant formation would be slightly reduced, around 0.75%, the increase of Natural gas consumption involves a higher weight on the total impact. As a result, it can be observed in the graph an increase on the total impact if the Scenario D would be implemented. The increase on the total impact is around 2%.

6.5 Painting process comparative results

Finally, the normalisation results for the global painting process on each Scenario were analysed to obtain a final comparison among all the different studied Scenarios.

The painting process normalisation data was analysed under four different criteria in order to select some of the impact categories to obtain relevant results.

First of all, results of all impact categories were analysed. After that, the more relevant impacts were selected. In order to do that, the impact categories with a weight above 2% with respect to the total were analysed. Both graphs, i.e. all impact categories and only the selected categories, show the same trend for the different Scenarios. The second criterion is represented in the next figure.

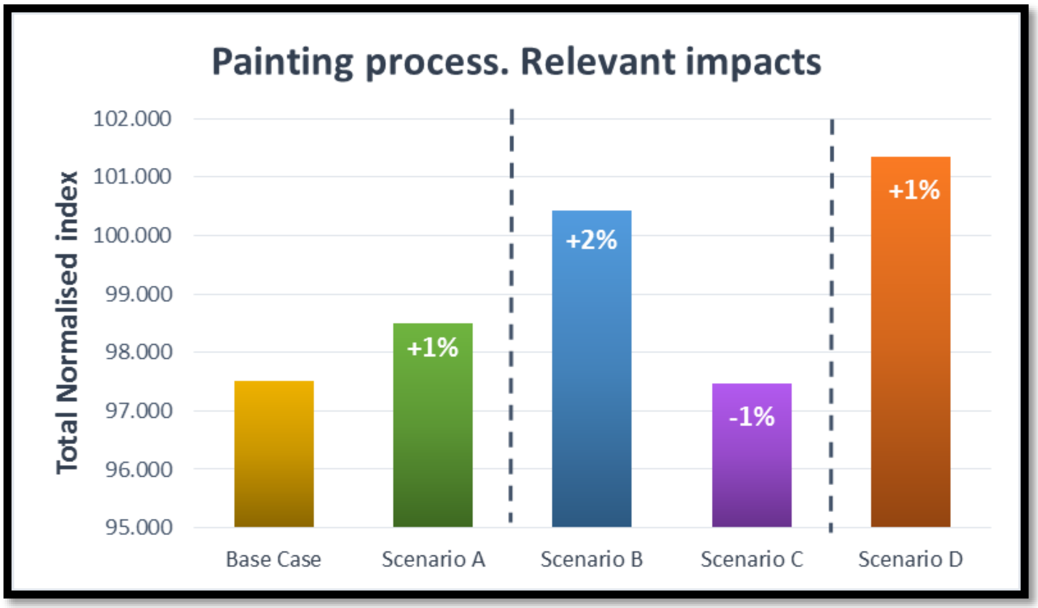

Fig.19. Normalisation data of the system Painting process evaluating the impacts with a weight higher than 2%.

The categories included for this evaluation were terrestrial acidification, freshwater eutrophication, human toxicity, particular oxidant formation, freshwater and marine ecotoxicity, natural land occupation and fossil depletion. All together represents around 95% of the total impact categories.

The total impact from the painting process increases with respect to the base case, by 1% at the current situation of the plant. Comparing Scenario A with the rest of Scenarios it can be seen an increase of the total impact on Scenarios B (2%) and a decrease due to Scenario C (-1%). Finally Scenario D involves an increase by 1% compared with Scenario B.

As it was explained before these increases or decreases in all Scenarios are strongly linked to the natural gas consumption. The impact is being reduced in some categories as human toxicity or photochemical oxidant formation due to the abatement of air emissions but other impacts as terrestrial acidification or natural land transformation are increased because of the natural gas consumption. As a result these variations reach an equilibrium being the impact practically the same as the initial situation.

Furthermore, focusing on the target of study, reduction on formaldehyde emissions, impact categories related with formaldehyde were taken into account for the next criterion. The same tendency was observed as it is shown in the figure 19.

Formaldehyde is strongly related to human toxicity, so that the results for this impact category were also analysed.

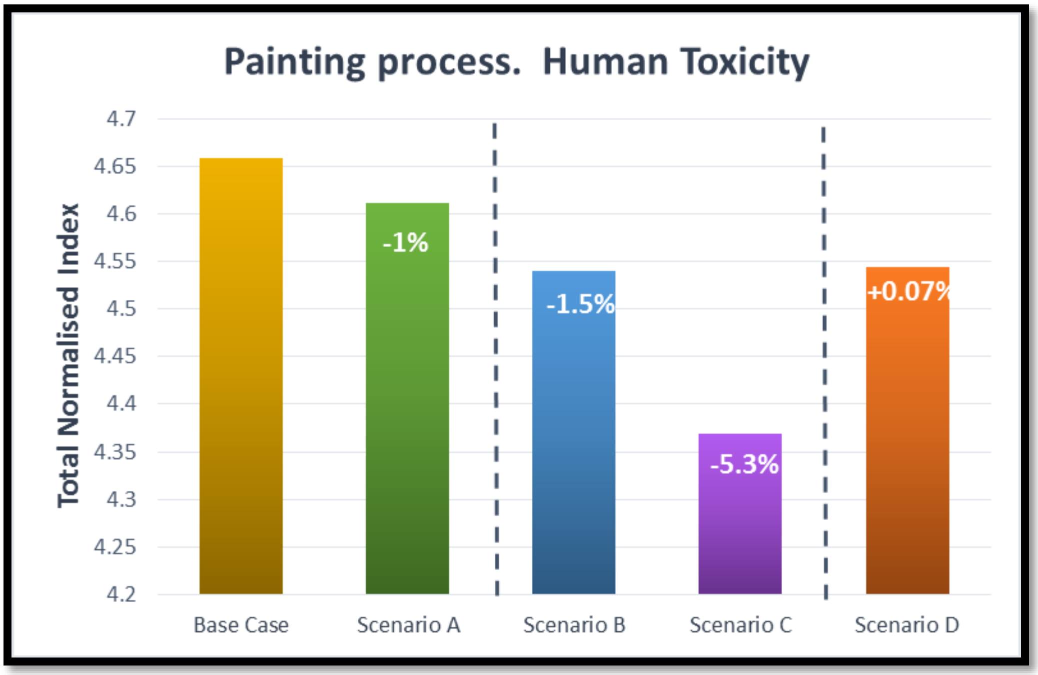

Fig.20. Human toxicity normalisation data for all the Scenarios studied.

One of the main goals of the study of the different Scenarios was to achieve a reduction on the Human toxicity impact through the formaldehyde air emissions reduction. In this last chart, is could be seen that the target is achieved in all Scenarios comparing them with the base case Scenario.

At the chat it can be seen that the current situation of the plant (Scenario A) accomplishes a reduction on the normalised index of human toxicity by 1%. Scenarios B and C improve the situation with regard to the Scenario A by 1.54% and 5.26% respectively, being the latter the most environmental sustainable Scenario. Scenario D does not involve a great change with respect to Scenario B. In fact, the human toxicity normalised index is slightly increased by 0.07%.

As it was observed on all the graphs, direct emissions are not the only component affecting human toxicity. Other inputs as the natural gas consumption and paints are related to this impact as well. Therefore, even though formaldehyde emissions can be almost eliminated due to these actions, the human toxicity impact cannot be completely reduced.

7. CONCLUSIONS

Through the Life Cycle Assessment, the following conclusions were obtained based on the analysis made in this work.

- Analysing the hot spots from the main painting processes, Electrocoating (ELPO) and Top coat processes cause the highest environmental impacts due to the use of the materials, natural gas and wind electricity.
- A possible future action to reduce the impacts based on the hot spots identified would be the research and development of different resins that can be used for the production of ELPO materials with a lower environmental impact by the paint producers, or a modification in their production process leading to a reduction in the CO_2 emissions.
- Scenario A is focused on the formaldehyde emission reduction in the Primer process and therefore a reduction on the human toxicity impact. Comparing the results from this Scenario (current situation of the plant) and the situation in 2015 (Base case Scenario), it can be determined that there is a decrease on the human toxicity impact by 7% in this process so the target of this improvement was achieved. Besides, terrestrial ecotoxicity is reduced. However, due to the increase of the natural gas consumption there is an increase on the rest of the impact categories.
- Scenarios B and C studied the installation of new abatement equipment for the Top coat ovens, RTO (Regenerative Thermal Oxidiser) or TAR (Recuperative Thermal Oxidiser) with energy recovery, to reduce VOC and formaldehyde emissions. Comparing both Scenarios with the current situation of the plant (Scenario A) at the Top coat process, it can be concluded that:
    - Natural gas plays an important role on all the impacts for Top coat process, what leads to an impact increase in Scenario B (4%), where the addition of new burners is needed. On the other hand, in Scenario C the natural gas consumption decreases and therefore the total impact is being reduced (2%).
    - Focusing the study on Human toxicity, a reduction is obtained with both Scenarios. Scenario B reduces human toxicity by 3% while Scenario C reduces it by 11%.

Although Scenario C has a higher reduction and therefore it is more environmental sustainable, both Scenarios achieve the target of the new formaldehyde classification.

  - From an economic point of view, Scenario B achieves the target of the company (formaldehyde and human toxicity reduction) and it is economically more favourable which explains the decision made by the plant of building an RTO.

- The future application of Scenario D to reduce VOC emissions at Base coat booths involves a high natural gas consumption. As it was previously seen, this entails an increase in the total impact, specifically the impact would be increased by 2% having into account the Top coat process.
- In the final comparison analysis performed for all different Scenarios, it has been observed that from the total impact and Human toxicity point of view the most environmental sustainable Scenario is the installation of incinerators (TAR) at Top coat process, i.e. Scenario C.

Finally, with this work and the results obtained it was proved that Life cycle Assessment is a powerful tool to analyse different improvement alternatives that can be installed in a vehicle painting plant from the environmental sustainability viewpoint.

8. BIBLIOGRAPHY

[1] Geldermann J. and Rentz O. (2005) *Decision Support through Mass and Energy Flow Management in the Vehicle- Refinishing Sector*. Journal of Industrial Ecology 8 (4). 173-187.

[2] STS BREF (2007). *Reference Document on Best Available Techniques on Surface Treatment using Organic Solvents*. European Commission. 6:163-186.

[3] Rivera J.L. and Reyes-Carrillo T. (2016). *A life cycle assessment framework for the evaluation of automobile paint shops*. Journal of Cleaner Production 115. 75-87

[4] EEA (2008). *Air pollution: Air pollution harms human health and the environment*. European environmental Agency. Available at https://www.eea.europa.eu/themes/air/intro (Last access on 02/2017)

[5] Heather L.M. and Lester B.L. (1998). *A life-Cycle Model on automobile*. Environmental Science & technology/news 322-330.

[6] Hernandez M., Messagie1 M. Hegazy O., Marengo L. Winter O. and Van Mierlo J. (2017). *Environmental impact of traction electric motors for electric vehicles applications*. Int Journal Life Cycle Assess 22. 54–65.

[7] Papasavva S., Kia S., Claya J. and Gunthert R. (2000). *Characterization of automotive paints: an environmental impact analysis*. Progress in Organic Coatings 43. 193–206.

[8] Regulation (EC) No 2015/491 of the European Parliament and of the Council of 23 March de 2015 amending Regulation (EU) No 605/2014 amending, for the purposes of introducing hazard and precautionary statements in the Croatian language and its adaptation to technical and scientific progress, Regulation (EC) No 1272/2008 of the European Parliament and of the Council on classification, labelling and packaging of substances and mixtures.

[9] Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control). Official Journal of the European Union.

[10]* **Confidential website***

[11] Omar M.A. (2011). *The automotive body manufacturing systems and process*. WILEY. UK. 2-5:15-233.

[12] RESOLUCIÓN de 7 de enero de 2014, del Instituto Aragonés de Gestión Ambiental, por la que se actualiza la autorización ambiental integrada de la planta de fabricación de vehículos a motor, ubicada en el polígono Entrerríos, en los términos municipales de Figueruelas y Pedrola (Zaragoza), y promovida por General Motors España, S.L.U. (Número Expte. INAGA 500301/02/2012/2990). Boletín Oficial de Aragón.

[13] Streitberg H.J. and Dössel K.F. (2008). *Automotive paints and coats*. 2° ed. VILEY-VCH. Verlag GmbH and Co. KGaA. Germany. 3-6: 61-210.

[14] ***Confidential report***

[15] Stoye D. (1993) *Paints, coatings and solvents*. VCH. Germany. 1:3-7; 2: 54-84; 3:101-124; 11:243-246

[16] Stoyer D. and Freitag W. (1996) *Resins for coatings*. HANSER. Germany. 6:103-118.

[17] Wicks Z.W, Jones F.N., Pappas S.P., Wicks D.a. (2007). *Organic coatings: Science and technology*. 3° Ed. WILEY-INTERSCIENCE. New Jersey.8: 159-166; 10-11: 200-229.

[18] Formacare**.** *Formaldehyde information.* Available at http://www.formacare.org/about-formaldehyde/ (Last access on 05/2017).

[19] Bolt H.M., Johanson G., Nielsen G. D., Papameletiou D. and Klein C. L. (2016). *SCOEL/REC/125 Formaldehyde. Recommendation from the Scientific Committee on Occupational Exposure Limits.* European commission.

[20] ***Confidential book***

[21] RAC (2012). *Annex 1: Background document to the Opinion proposing harmonised classification and labelling at EU level of Formaldehyde.* Committee for Risk Assessment.

[22] Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006.

[23] UNE-EN ISO 14040: 2006. *Environmental management. Life cycle assessment. Principles and framework*. Ginebra: International Organisation Standardisation.

[24] UNE-EN ISO 14044:2006. *Environmental management. Life cycle assessment. Requirements and guidelines.* Ginebra: International Organisation Standardisation.

[25] Herbert F Lund (1971) *Industrial Pollution Control Handbook*. McGraw-Hill. USA. 7:1-10.

[26] CMM. *Regenerative and Recuperative Thermal oxidiser information*. Available at

http://www.thecmmgroup.com/ (Last access 05/2017).

[27] Geldermann J. and Rentz O. (2005) *Multi-criteria Analysis for Technique Assessment Case Study from Industrial Coating* Journal of Industrial Ecology 9 (3). 127-142.

[28] Goedkoop M., Heijungs R., Huijbregts M., De Schryver A., Struijs J. and van Zelm R. (2013) *ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level*. Ministerie van VROM Rijnstraat.

[29] ILCD (2010). *Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment. Background document.* European Commission. Joint Research Centre. Institute for Environment and Sustainability.

[30] ILCD (2010). *Framework and requirements for Life Cycle Impact Assessment models and indicators*. European Commission. Joint Research Centre. Institute for Environment and Sustainability.

[31] ENDESA (2015). *Informe anual 2015*. Documento resumen.

[32] ***Confidential website***

[33] UNE-EN ISO 14045:2012 *Environmental management. Eco-efficiency assessment of product systems. Principles, requirements and guidelines.* Ginebra: International Organisation Standardisation.

[34] INE. *IPC data from the last ten years*. Available at http://www.ine.es/jaxiT3/Tabla.htm?t=22344 (Last access 06/2017)

[35] OMIP. *Natural gas price 2018*. Available at http://www.omip.pt/ (Last access 06/2017)

ANNEX

The original version contains 5 annex with detailed information from the plant of study. Those annex were:

Annex 1: Flow diagram from the whole process

Annex 2: Natural gas allocation for the base case.

Annex 3: Natural gas variation for the different scenarios calculation.

Annex 4: VOC balances.

Annex 5: Economic analysis.

The content of these annexes is confidential, so they cannot be exposed on the public version