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A framework for environmental and energy analysis of the automobile painting process

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Abstract

The automobile industry is experiencing many challenges that affect its sustained growth. The increasing cost of energy used at production plants is often identified as one of the main challenges. Environmental regulations also pose pressure on industry. Within the automobile manufacturing stages, the painting process is the most energy intensive. In this work, a framework for a European collaborative project is presented. The utility of the framework is briefly presented to highlight improvement opportunities to lower energy consumption and environmental impact of a plastic part paint shop.

Keywords: automobile painting processes, environmental impact, energy consumption

1. Introduction

Transportation is an integral part of society. Through the utilization of automobiles, airplanes, trains, and boats people around the world have been able to discover new horizons. At an individual, more personal level, the automobile has become a necessity and an indispensable tool for social development.

Three different perspectives are used to describe the context of the automobile, Fig. 1.

From a societal perspective, the automobile has enhanced the mobility of people. Owning an automobile provides a certain level of freedom that other means of mobility such as airplanes and trains do not provide. The automobile gives the owner a feeling of control. In certain societies it may signal acquisition of power or development level.

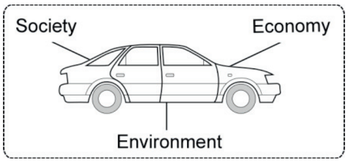

Fig. 1 Perspectives of the automobile.

From an economic perspective, the automobile is a source of employment. At the local level, it leads to economic activity by allowing people to connect with other sectors and markets of society. In other ways, the supply chain of the automobile leads to the creation of small businesses and ignites demand for economic flow, trade, research, collaborations, and innovation.

From an environmental perspective, the automobile is a source of anthropogenic pollutants. Manufacturing activities require the input of raw materials and water, and the required processes are often energy intensive. The usage of an automobile leads to the emissions of air pollutants including for example benzene, acetaldehyde, and formaldehyde. The maintenance, repair, and disposal can potentially lead to the emission of unwanted effluents such as oils and metals [1].

Due to the economic nature of market, industry often fails to continuously improve its performance for each perspective,

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more specifically the environmental. The life cycle of an automobile includes stages that range from component manufacturing to end-of-life, shown in Fig. 2. Life cycle use stage (vehicle driving) carries the most environmental impact, responsible for up to 75% of the total impact [1]. This impact is associated with the combustion of the fuel, and is mainly due to CO_2. Government has become an external driver for environmental change. In the USA, the CAFE standards have pushed industry to enhance the fuel efficiency of automobiles (kilometers traveled per liter of fuel). In 2007 the European Union enacted REACH (Registration, Evaluation, Authorisation, and Restriction of Chemical substances), a law that regulates the usage of chemicals by industry [2]. As for the automobile industry, the painting shop is the most affected. Hence, there is a need to improve the environmental performance of painting activities.

A balance life cycle approach is needed to understand trade-offs and other consequences of each system change option. Different strategies may be followed to analyze the painting process. Process oriented, material oriented, or combination approaches could be considered to devise the main key materials, processes and configurations that would meet both environmental and product quality constrains in order to provide the basis for decision-making.

The work presented here is part of a collaborative project (industry R&D and academia) that seeks to establish an integrated and strategic approach to improve the overall performance of the painting shop. The objective of this paper is to introduce a framework to ease the environmental characterization and improvement of the painting shop. The environmental profile of the painting processes is presented and discussed. The application of the framework is presented, identifying opportunities and areas for improving energy consumption and lowering environmental impacts.

2. Environmental profile of the painting shop

Traditional automobile paint consists of three layers: primer, base, and clear (varnish), for both metal and plastic surfaces. The paint serves several purposes. On the one side the paint makes the auto appealing to customers. On the other side, the paint provides weather, wear and scratch resistance. The processes and materials needed to meet these purposes are not exempt of environmental impacts.

Volatile Organic Chemicals (VOCs) are targeted by REACH. The majority of VOCs emissions in the automobile life cycle are emitted during the manufacturing stage, and the painting stage is responsible for 95% of the emissions [3].

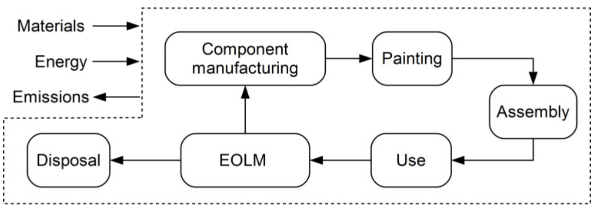

Fig. 2. Generic life cycle stages for an automobile. Dotted line represents the boundaries of the system, solid lines are stages, and arrows represent flows. EOLM stands for end-of-life management (reuse, recycle, and disposal).

The paint shop carries the greatest environmental load among all manufacturing stages of an automobile [4]. Up to 90% of emissions from automobile manufacturing have been associated to the painting stage [6]. Painting activities may be responsible for up to 95% of VOC emissions [3]. Solvents used in paints/coats formulations are the main source of these emissions. The energy required to paint an automobile lies between 5-15 GJ, depending on size (compromising paint application and material production) [5]. Painting processes, including surfaces preparation, paint application and drying, consume 48 to 60% of the energy required for assembling an automobile [7,8].

Emissions from painting processes that lead to environmental impact include emissions to air, water (paint overspray), and soil (paint sludge) [9]. Air emissions include PM, VOCs, SOx, NOx, CO, and CO_2 [4]. The greatest concern in the painting process is the emission of VOCs. When exposed to sunlight and nitrogen oxides VOCs form ozone and smog due to photochemical reactions [6].

3. Methodology

The core of the following methodology is based on the application of life cycle thinking philosophy to characterize and improve the environmental impact of the painting stage. Fig. 4 shows the proposed framework. Using a project planning approach, the framework starts with the description of objectives. For the painting stage, the objectives are to improve energy efficiency and to lower emissions. Implementation of solutions may find their way in the short and long-term, depending on several factors like technical limitations and economics. Life cycle planning is applied to set the path of the research. In this step, critical macro aspects of the system are identified. Different strategies may be followed to analyze the painting process. Strategies including material oriented, process oriented, or a combination are considered to devise the main key materials, processes, and configurations that would meet both environmental and product quality constrains.

Analysis of each track starts with a benchmarking. The aim here is to learn from the literature and identify important improvements/achievements from previous work. Industry trends are also investigated. The knowledge gained from benchmarking is used to delineate possible solutions. Initially, solutions for each track are sought while leaving the other track fixed. That is, devising solutions for materials without changing the processes. The proposed solutions are then compared from theoretical and practical perspectives. Here, knowledge from the "operational floor" is used to identify technical limitations and short/long-term possibilities. Scenarios for materials, processes, or a combination of the two are defined and analyzed using the life cycle assessment methodology. Results are verified against the objectives, and the process is repeated until feasible solutions (base on technical, economic, and practical factors) are found.

The framework seeks to fulfill two main goals: (i) providing guidance for characterizing the environmental performance of the current paint shop, and (ii) providing

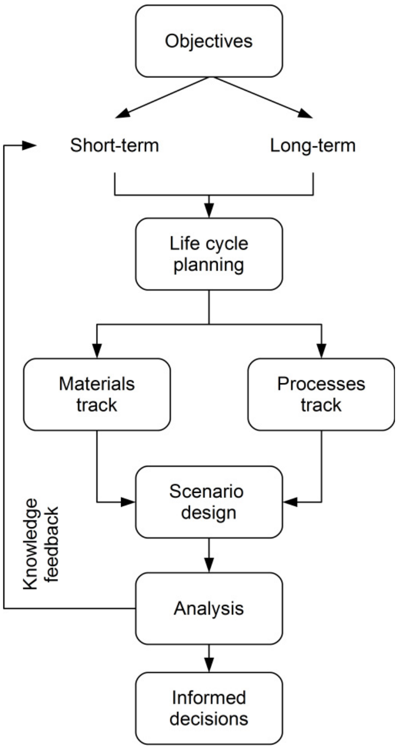

Fig. 4. Framework to enhance environmental performance during R&D.

guidance to incorporate environmental analysis early in the development of a new paint shop configuration.

4. Case study

Painting processes for automotive metal body and plastic surfaces differ. Painting of plastic surfaces often takes place in a different plant and are subsequently delivered to the assembly plant. A European collaborative project was started with the objective of improving the material and resource efficiency of the paint shop. The case study describes a painting shop of plastic parts by a French manufacturer. The manufacturer paints bumpers for several automobile makers. The painting shop consists of a sequence of stages, shown in Fig. 3. Due to present limitations to characterize the full reference system, a complete life cycle approach is not possible at this stage of the project. Hence, only unit processes for which data are available are discussed.

4.1. Materials track

Liquid coats include solventborne and waterborne. The solvents used in these coats may include: urethenes, epoxies, polyesters, acrylic, and high and low temperature waterbornes [12]. Polyesters and acrylic are commonly-used solvents in waterborne coats. Main resins used for waterborne coats are: acrylics, epoxies, alkyds/polyesters, polyurethanes, and alkyd emulsions [13]. More complete thorough descriptions of the composition of coats are given by [10,14,15].

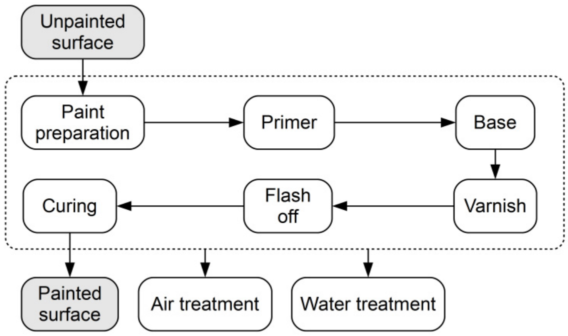

Fig. 3. Sequence of stages for painting a plastic surface.

Solvents used in paints/coats formulations are the main source of VOC emissions. Waterborne paints still contain levels of VOC (3.1 to 4.6 kg/gallon [12]); or up to 15% of formulation [10]; solvent is needed to ease adhesion and fluidity of the material [6]. High temperature cured coatings have less VOC per gallon while low temperature curing requires less energy [12]. Waterborne primers are also sensitive to humidity [16]. In terms of paint choices to decrease VOC emissions, previous studies found no clear environmental advantage from switching from solvent to waterborne paints [17–19].

The current paints used at the shop are all solventborne. In the short term, switching to other paint type is not a viable solution, as determined by the industrial partners. Meanwhile, work is underway to develop new formulations with enhanced environmental performance.

A material flow analysis was conducted to identify the main inputs to each stage. Values for energy, paint consumption, and air and liquid waste were documented. The resulting material and resource inventory is being validated. The next step will consist of using the life cycle methodology to characterize the environmental impact from both the production of materials and resources as well as the outputs of the paint shop.

4.2. Processes track

The literature was consulted to identify “hot spots” of the painting stage. For a solventborne configuration, Roelant et al. [9] reported that about 50% of the energy is consumed by heating the air booth and ovens for base and clear coats. On a different study, Moign [10] reported that energy required for spraying, using a plasma spraying process, was responsible for about 70-80% of total electricity consumption. The conditioning of the paint booth and oven has been the target of other studies [22,23]. In a most recent study, Li et al. [24] reported on a computational technique to facilitate the redesigning of the ventilation system and improving energy efficiency.

The findings from the literature were compared with the paint shop inventory. Table 1 the energy allocation for the case study. Data is given on a percentage basis due to confidentially. The research team identified the curing oven

Table 1. Energy allocation for case study.

Process	Electricity (%)
Paint preparation	10
Primer application	6
Base application	12
Varnish application	12
Flash off Air treatment	32
Curing	22
Water treatment	6

and transfer efficiency as two key aspects of the paint shop that needs to be targeted in the short term.

4.2.1. Curing stage

A priority of the industrial partners is to lower working temperature of the varnish oven. With the current clear coat this action will require a longer curing time. Another option is to change the paint formulation to (i) reduce curing time and/or (ii) reduce layer thickness. At this time, the new varnish is still in development. The initial attempt is to quantify the gain in environmental performance that will result from a temperature change, assuming a fixed curing time. In Fig. 5 two cases are presented: Case 1 describes the current operating conditions and Case 2 the proposed change, decreasing temperature by 20°C. Both cases use a natural gas boiler to condition the oven. The energy consumption of Case 2 is expected to be reduced by 35%. This analysis will nurture from previous studies on multi-objective optimization to consider both process parameters and environmental analysis [25]. The question that rises is: what are the implications of lowering the oven temperature? There is a need to describe how the drying time, energy consumption, surface quality, and VOC emissions will be affected.

4.2.2. Transfer efficiency

Transfer efficiency (TE) refers to the percentage of paint that deposits on the surface. For typical liquid paints, about 40-50% of the coats material is oversprayed (material that does not deposit on the surface). The overspray needs to be recovered, handled, and disposed of (as paint sludge).

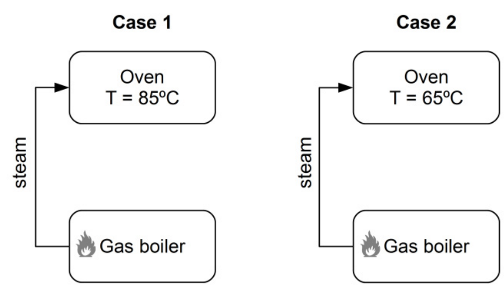

Fig. 5. Schematic of cases considered for a varnish oven operation with representative values. Data represent 1 year of operation.

Table 2. Transfer efficiency (TF) per layer.

Layer	TF (%)
Primer	43
Base	36
Varnish	50

Material consumption and cost are two main aspect of the paint application. An approach to improve TE is to switch liquid paints for powder. For powder paints the material could be recovered and reused [10], and transfer efficiencies of up to 97% could be achieved [14]. In the short term, switching to powder paint is not viable due to the cost of upgrading to new equipment. TE can also be increased by using a voltage block bell system [21]. For the case study TE values are presented in Table 2.

Members of the research team are searching for ways to improve the application process. The key aspects under consideration are: number of robots, type of spraying pistol, and process parameters like pressure. The overall goal is to decrease both energy and paint overspray.

4.3. Integrated system

Fig. 6 shows the proposed combine process sequence. The integrated approach uses two layers by combining the base and varnish. A potential reduction on energy consumption of 23% was identified in the benchmarking, along with a layer thickness reduction of 35 µm [26]. These values are used as reference point. Table 3 shows preliminary results for both the reference and integrated systems. The software Gabi 6 was used to calculate the contribution to selected impact categories. To describe the European context the recommendations by the European Commission-Joint Research Centre - Institute for Environment and Sustainability framework were followed. The impact methods used were: climate change (IPCC 100 years), ozone formation (steady-state ODPs 1999 as in WMO assessment), and photochemical ozone formation (LOTOS-EUROS as applied in ReCiPe).

With the expected energy reduction, the integrated system may have reduced contributions to climate change by 19.69%,

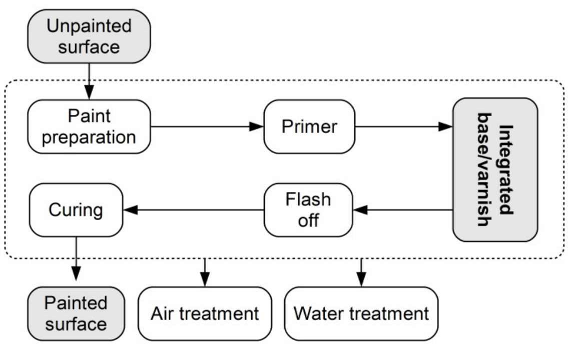

Fig. 6 Integrated painting stage.

Table 3 Preliminary results from integrated system.

Impact category	Unit	Reference system	Integrated system
CC	Kg CO2 eq	1.27	1.02
OD	Kg CFC 11 eq	1.63E-8	1.25E-8
POF	Kg NMVOC	2.97E-3	2.38E-3

CC= climate change, OD=ozone depletion, POF= photochemical ozone formation

ozone depletion by 23.31%, and photochemical ozone formation by19.87%.

5. Summary

Making improvements to large manufacturing processes is faced with many challenges. Complexities are both theoretical and practical. To find novel solutions to the energy consumption and environmental impact of painting processes a multidisciplinary project, in collaboration with industry, academia and research institutes, was established. The main objective of the project is to provide stakeholders in the automobile industry with knowledge to enhance the decision-making process for material selection and process design associated with painting activities. It is expected that projects outcomes will provide the basis to better incorporate environmental analysis early in the development of future system changes.

The project began with the definition of very specific objectives in terms of quantitative environmental performance targets. The presence of both short and long-term solutions is currently a challenge.

This paper identified and described the challenges and complexities that will be faced during the implementation of the project. Notably, solutions are very dependent on the configuration of the system. The environmental aspects are expected to be given greater weight than in previous projects. At the same time, the feasibility of the proposed solutions will also depend on cost. Therefore, to improve the value of the project and actions taken by industry, it is important that trade-offs are taken into consideration both for short and long-term impacts.

The framework is expected to be integrated, i.e., to consider broader aspects of the system. To achieve this goal, the research team is looking for ways to incorporate non-material aspects to the project. Two aspects identified at present are the “level of innovation” and the “value added” to the overall business. Ways to quantify these two aspects are being sought. By considering non-material broader aspects, the project will also incorporate the three perspectives shown in Fig. 1. The preliminary framework will be updated to consider these broader aspects as the project matures.

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