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Simulation of Energy Savings in Automotive Coatings Processes

Marco Gerini Romagnoli
University of Windsor

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by

Marco Gerini Romagnoli

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Simulation of Energy Savings in Automotive Coatings Processes

by

Marco Gerini Romagnoli

APPROVED BY:

____

Dr. E. Tam
Department of Civil and Environmental Engineering

____

Dr. G. Rankin
Department of Mechanical, Automotive, and Materials Engineering

____

Dr. A. Sobiesiak, Co-Advisor
Department of Mechanical, Automotive, and Materials Engineering

____

Dr. P. Henshaw, Advisor
Department of Civil and Environmental Engineering

September 9th, 2016

Declaration of Originality

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication.

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Abstract

Recently, the automakers have become more and more aware of the environmental and economic impact of their manufacturing processes. The paint shop is the largest energy user in a vehicle manufacturing plant, and one way to reduce costs and energy usage is the optimization of this area. This project aims at providing a tool to model and simulate a paint shop, in order to run and analyze some scenarios and case studies, helping to take strategic decisions. Analytical computations and real data were merged to build a tool that can be used by FCA for their Sterling Heights plant.

Convection and conduction heat losses were modeled for the dip processes and the ovens. Thermal balances were used to compute the consumptions of booths, decks and ovens, while pump and fan energy consumptions were modeled for each sub-process. The user acts on a calendar, scheduling a year of production, and the model predicts the energy consumption of the paint shop.

Five scenarios were run to test different conditions and the influence of scheduling on the energy consumption. Two different sets of production schedules have been evaluated, the first one fulfilling the production requirement in one shift of 10 hours, at high rate, the second one using two 7-hour-long shifts at medium production rate. It was found that the unit cost was minimized in the warmest months of spring and fall, and system shutdown was a crucial factor to reduce energy consumption. A fifth hypothetical scenario was run, with a 4 month continuous production and an 8 month total shutdown, which reduced the energy consumption to a half of the best realistic scenario. When the plant was run in a two-shifts configuration, the cost to coat a vehicle was found to be \$29 with weekend shutdown, and \$39 without. In the one-shift configuration, the cost was slightly higher, but the difference was less than 5%. While the fifth scenario showed a consistent reduction of the unit cost, inventory and logistic expenses deriving from the production strategy make this scenario almost impossible to realize. A sensitivity analysis was run on several parameters influencing the energy consumption of the paint shop, and the booths set point temperature was found to be the most significant factor.

To the power of knowledge

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List of Abbreviations

ARU	Air Recirculation Unit
ATU	Air Treatment Unit
CAB	Cellulose AcetoButyrate
CAFE	Corporate Average Fuel Economy
COP	Coefficient Of Performance
CRF	Centro Ricerche FIAT (FIAT Research Center)
DC	Direct Current
DES	Discrete Events Simulation
EC	Electro-Coating
E-Coat	Electro-Coating
EX	exhaust
FA	Fresh Air
FCA	Fiat Chrysler Automobiles
FIS	Factory Information System
h	hours
HP	horsepower
HVAC	Heating, Ventilation and Air Conditioning
INF	infiltration
JPH	hourly production rate (Jobs Per Hour)
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LEL	Lower Explosion Limit
MPG	Miles Per Gallon
MS	Microsoft®
NAD	Non Aqueous Dispersion
PSI	Pounds per Square Inch
PT	Pre-Treatment
RTO	Regenerative Thermal Oxydizer
SHAP	Sterling Heights Assembly Plant

SI	Système International d'Unités (International Units System)
TP	throughput
UDF	User Defined Function
UF	Utilization Factor
US	United States
UV	Ultra-Violet
VOC	Volatile Organic Compounds
WIP	Work In Progress

List of Symbols

β	coefficient of volume expansion [1/K]
Δp	pressure drop [Pa]
ΔT	temperature difference [K]
$\epsilon_{ATU,h}$	ATU efficiency of heating cycle [-]
ϵ_{fan}	fan efficiency [-]
ν	kinematic viscosity or momentum diffusivity [m^2/s]
ρ_{bath}	density of the bath fluid [kg/m^3]
Φ_{ev}	evaporation rate [kg/s]
A	surface area [m^2]
c_{bath}	specific heat capacity of the bath fluid [J/kg·K]
c_{cb}	specific heat capacity for the car body material [J/kg·K]
$c_{carrier}$	specific heat capacity of the carrier [J/kg·K]
c_p	specific heat capacity at constant pressure [J/kg·K]
c_{p_a}	specific heat capacity of air at constant pressure of air [J/kg·K]
E_v	illuminance [lm/m^2]
F	ovens' correction factor [-]
F_{cb}	correction factor for the car body heat capacity [-]
g	gravity acceleration (9.81 m/s^2)
h	heat transfer coefficient [$W/m^2 \cdot K$]
h_i	heat transfer coefficient for the inner surface [$W/m^2 \cdot K$]
h_o	heat transfer coefficient for the outer surface [$W/m^2 \cdot K$]
k	material thermal conductivity [W/K·m]
K	luminous efficacy [lm/W]
L_c	characteristic length [m]
$m_{carrier}$	mass of the carrier [kg]
m_{cb}	mass of the car body [kg]
$\dot{m}_{EX}$	exhaust air mass flow rate [kg/s]
$\dot{m}_{FA}$	fresh air mass flow rate [kg/s]
$\dot{m}_{INF}$	infiltration air mass flow rate [kg/s]

Nu	Nusselt number [-]
p	probability [-]
P	power [W]
P_{comp}	compressor power [W]
P_l	lights power consumption [W]
Pr	Prandtl number [-]
$\dot{Q}_{ATU,NG}$	rate of natural gas energy used in the ATU [W]
$\dot{Q}_{cb,dip}$	rate of heat loss due to the car body heat capacity in the dip processes [W]
$\dot{Q}_{cb,ov}$	rate of heat loss due to the car body heat capacity in the ovens [W]
$\dot{Q}_{cool}$	rate of thermal energy withdrawn by the airflow [W]
$\dot{Q}_{heat}$	rate of thermal energy supplied to the airflow [W]
$\dot{Q}_{loss}$	rate of heat loss by the control volume due to the losses [W]
$\dot{Q}_{NG}$	rate of heat added to the control volume [W]
$\dot{Q}_{overall}$	overall heat transfer [W]
Q_{su}	startup energy consumption [J]
Ra_L	average Rayleigh number along the surface length [-]
Re	Reynolds number [-]
T	temperature [K]
T_{amb}	ambient temperature [K]
T_b	bath temperature [K]
T_{out}	outside air temperature [K]
T_{ov}	temperature inside the oven [K]
T_{plant}	plant temperature [K]
T_{w_i}	temperature of inside wall surface [K]
T_{w_o}	temperature of outside wall surface [K]
T_∞	temperature of the air or fluid far from the surface [K]
U	overall heat transfer coefficient [$W/m^2 \cdot K$]
v	velocity [m/s]
$\dot{V}$	volume flow rate [m^3/s]
V_{bath}	volume of the bath [m^3]

x absolute humidity [kg_{H2O}/kg_a]

x_s absolute humidity at saturation [kg_{H2O}/kg_a]

1 Introduction

Fuel consumption has become a very important topic for automakers all over the world. Local and global regulations effectively forced the car manufacturers to improve their technology, massively investing in their research departments, to lower the fuel consumption of their products.

The United States of America enacted the Corporate Average Fuel Economy (CAFE) Standards in 1975, to improve the average fuel economy of the vehicles sold in the United States. According to the Summary of Fuel Economy Performance, written at the end of 2015 by the U.S. Department of Transportation, the CAFE standards were able to take the average fuel economy of the total fleet (i.e. including imported and domestic passenger cars and light trucks) from 19.9 MPG in 1978 to 31.5 MPG in 2014. [1]

While industry efforts to improve fuel efficiency are well known, less has been said about the impact that the production process has on the "Carbon Footprint" of a vehicle. Companies are becoming more and more sensitive to the idea of sustainability, and they are self-regulating to lower the energy involved in the manufacturing of their vehicles. Keeping the car production process carbon footprint low helps both in decreasing the cost of the vehicle for the manufacturer and in developing the idea of a sustainable future for the subsequent generations.

A step further in this direction is the analysis of the lifecycle impact of a product. It takes into account the environmental impact of a vehicle throughout its whole life, from raw materials extraction to waste treatment and recycling. The manufacturing process of a vehicle then becomes a part of every consideration regarding the environmental impact of the product. According to a study by Leven and Weber of the University of Stuttgart [2], the production of a car can account for about 3 MWh of energy use, based on data collected exclusively in German plants. Taking the gasoline heating value as 47,300 kJ/kg and its density as 0.755 kg/L, that value would correspond to the energy contained in approximately 302 L of fuel. Going deeper into speculations, if a mid-size car mileage is 15 km/L and the average annual distance per driver in the United States [3] is 21,000 km, that amount of energy – and consequently of gasoline – would allow that car to be driven for more than 4,500 km or approximately two and a half months. This value is expected to increase as vehicle efficiency improves. Although this is a rough estimation, it gives an idea of the real impact of the car manufacturing process and of why the analysis of it is becoming more and more a central topic in the automotive landscape.

To better focus the efforts for improvements in this field, it is important to break down the energy use in the various macro-areas that make up a vehicle production process: it is not enough to analyze the body shop, the paint shop, the assembly as a whole, to effectively address the problem it is fundamental to go deeper in detail into these areas. In the ENERGY STAR® guide [4], it is stated that up to 50% of the whole energy related to the production of a vehicle is used for coating. The electric share of the coating energy is mainly used to power the fan motors, and the fuel is used to condition the process air and for the thermal oxidation of VOCs in the exhaust. As will be discussed in the next sections, part of the paint shop energy consumption is due to the toxic nature of the materials.

Figure 1.1 shows the electricity usage in the macro-areas of a car manufacturing process. The diagram confirms, as already discussed, the energetic impact of the paint shop.

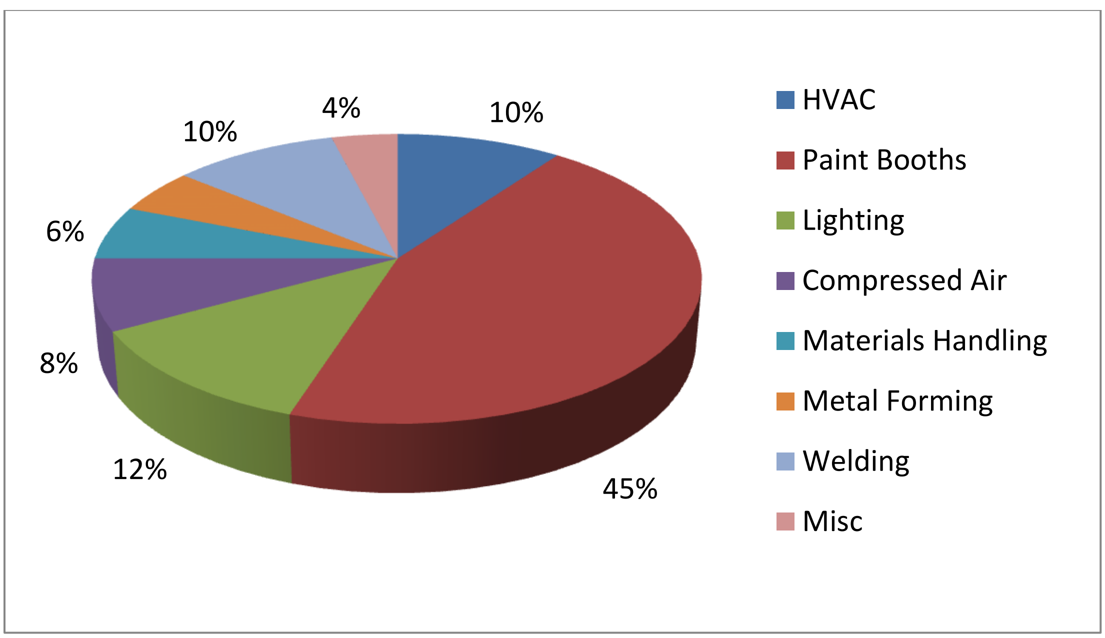

Figure 1.1 – Electricity consumption portions in areas of a vehicle assembly plant [4], [5]

Figure 1.2 is the result of Dürr's analysis of the trends in the automotive paint industry [6]. It shows the variety of energy carriers in use in the different areas of a paint shop, and their impact on the total cost. It is clear that the pretreatment has a very high consumption of hot water, while booths and ovens use most of the electricity and natural gas of the whole process. This is due to the nature of the operations: pre-treatment typically uses large dip tanks and the temperature of the phosphating bath has to be controlled and maintained in a certain range, while in the booths large air flows have to be treated and conditioned in order to keep the temperature and the humidity within the set point window.

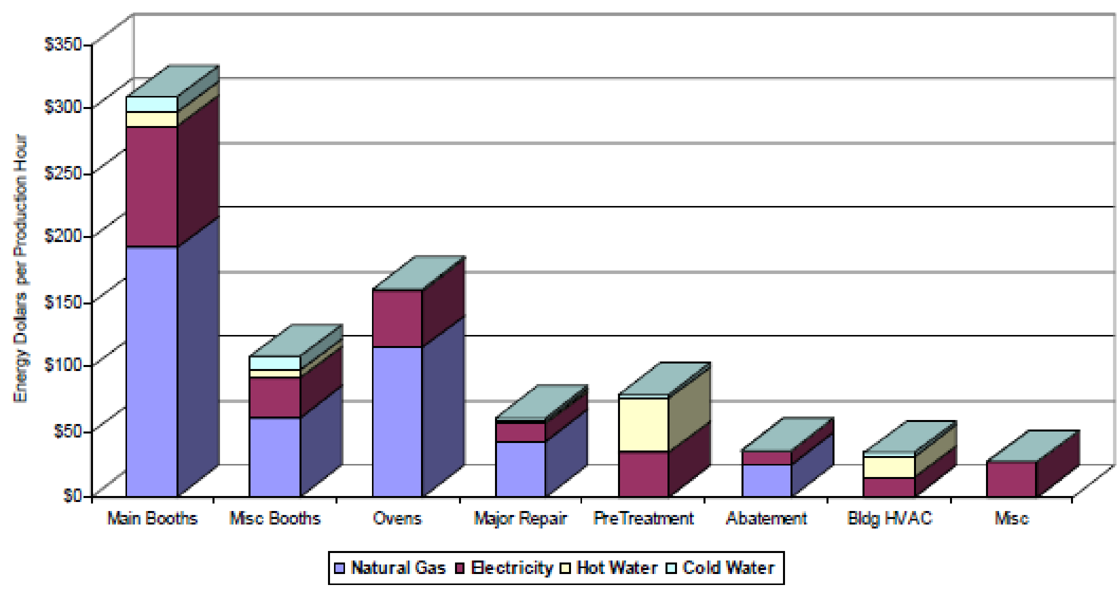

Figure 1.2 – Energy carriers used in paint shop processes [6]

Figure 1.3, shows the trend of the distribution of the expense for fuel (natural gas and heating oil) and electricity during the years for US vehicle assembly plants. It's noticeable that the proportions between fuel and electricity expenditures have kept almost constant. Although the chart shows the trend until 1994, nowadays the situation is very similar [7], [8], [6].

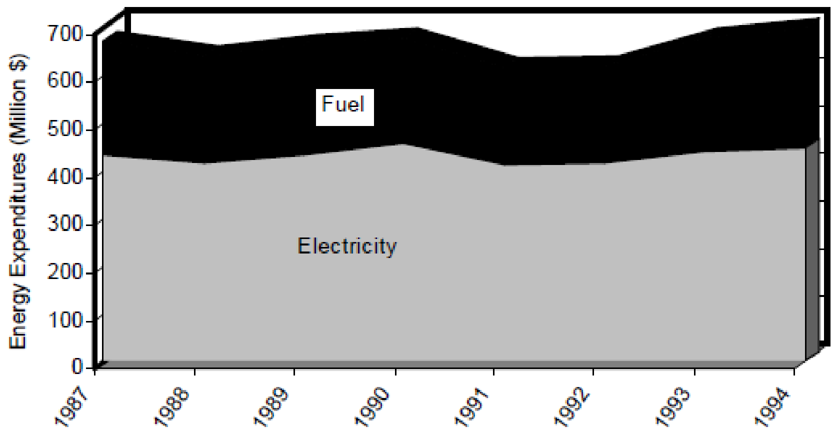

Figure 1.3 – Total fuel and electricity use in US assembly plants [4]

1.1 Objectives

This project aims at generating a tool that could help the engineers and the professionals that are involved in strategic decisions for energy reduction in vehicle assembly plant paint shops. This tool will then be used to run various production strategy scenarios and differentiate between their energy consumption.

1.2 Scope

The tool is an analytical model, generated for the Sterling Heights Assembly Plant (SHAP) of FCA. The scope of this project is to model all the steps of the coating process that are directly involved in the production. Therefore, building HVAC, lighting of some sections, and whole substations that are not linked to the main flow of production are not included in the model. Furthermore, some other stations that contribute to a small part of the overall energy consumption and for which it is not easy to get information, are included as “black boxes” - simply added to the partial result to deliver the final outcome without significantly affecting its accuracy.

Moreover, this project consists of the generation of a virtual environment in which data of the equipment currently installed in the paint shop can be inserted, and their operations can be simulated, while collecting the results of their energy consumption. This environment works by being coupled to the theoretical model, on the same schedule, and the cumulative energy consumption of every process in the paint shop can be analyzed.

2 Literature Review

Prendi et al. in their study "Life Cycle Inventory of the Automotive Paint Processes" [9] state that "As recognized by many authors, the most difficult part of the LCA [Life Cycle Assessment] is data collection, the part of the LCA known as the life cycle inventory (LCI)". The complexity of this kind of analysis explains the increasing focus on this matter, and the same authors, in their "Life Cycle Inventory E-Coat and Data Application Protocol for the Automotive Paint Processes" [10], published one year later, relate the energy and water use and the materials usage with the painted surface area in three of the paint process phases: pretreatment, e-coat and topcoat. Their study shows that while the e-coat water and materials usage are substantially higher than for the topcoat, in terms of the energy involved, the situation is the opposite. The e-coat process, in fact, uses at least one large dip-tank in which the body is submerged, as well as several spray rinses. On the other hand, the topcoat energy use is almost six times higher than that of the e-coat. This is explained by thinking of a spray booth operation: a strong downdraft is needed, with air temperature and humidity that have to be inside a narrow set-point window, leading to high power consumption for ventilation and air treatment.

2.1 Coating

The coating of a vehicle is the most direct quality factor that the customer can easily and immediately evaluate. It is not a simple layer of paint sprayed on the Body In White.

Painting a car body has two purposes:

- Aesthetic, since the finish of a vehicle is the most direct quality factor that the customer can easily and immediately evaluate. There are several types of coating, depending on the desired result: solid, metallic, and pearlescent coatings can be used to get the desired appearance.
- Physical, since coating a vehicle is fundamental to protect the body against corrosion, deterioration and contamination by external agents such as weather, chemicals, salt and sunlight.

The paint of a finished car is the result of a very complex process, with surface treatments, dip baths, multiple sprayed layers and heat curing. The painting process consists then of a multitude of sub-phases, each being responsible for manpower and asset utilization, resource allocation and energy consumption. Figure 2.1 shows the layers that usually make up a vehicle coating, with their average thickness [7].

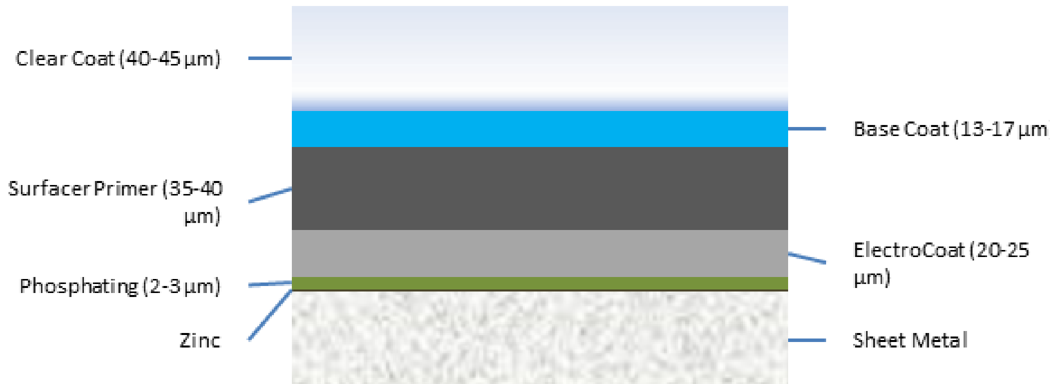

Figure 2.1 – Typical vehicle coating layers [7]

While developing a tool that allows one to analyze, simulate and estimate the energy use in such an intricate process is extremely important for any car manufacturing company, usually the complexity of the task acts as a discouraging factor, limiting the developments in this sense. Whenever anybody has to deal with the creation of a model of a determined part of the real world, the knowledge of the underlying principles has to be solid enough to guarantee good execution of the project. That is the reason why a section about coatings, coating processes and their new development, as reported in the literature has been included in the following sections.

2.1.1 Primers

Corrosion is a major issue for the car body. Because of its particular duty, it is subjected to many kinds of external contamination, and the primer layer is one of the main “defense lines” against deterioration. Prior to applying the primer layer, the welded body is pre-treated to prepare the surface for painting. Phosphate treatment passivates the metal surface. The subsequent primer layer does not just protect against corrosion and chemical damage; another important purpose of priming in the automotive industry is to resist mechanical damage, sometimes referred as “chipping”, of the paint film and to stop its propagation to the metal substrate.

Moreover, it is important to remember that the aesthetic result of the paint coating is of primary importance. A car with a finish that is very effective for metal substrate conservation but with a very poor appearance gives the customer the unavoidable feeling of poor quality, and can easily be the discriminant for the vehicle purchase. Another of the primer's purposes is then the reduction of the roughness of the metal profile, preparing the car body for the topcoat.

While the way the primer is applied on the surface will be discussed later, it is of some interest to go a little bit into the detail of the paint formulation. There has been a big evolution from the beginning of the twentieth century, and even nowadays there is not a prevalent technology. The choice of the manufacturer is still the main factor for the adoption of one paint technology instead of another [11].

In the 1960s Ford introduced a revolutionary system for the undercoating of the car bodies: electrodepositon, or electrocoating, has probably been the most significant change in the coating technologies over the years. In e-coat, paint is the solute of an aqueous solution, and the resin exists as positive or negative ions, depending on the technology used – anodic or cathodic. The paint resin with its ionic groups means the resin is soluble. The car body is charged by a direct current, and dipped into the tank filled with the solution. The coating ions migrate to the car body surface, and lose their charge leaving a neutral charge film. Electroendosmosis occurs, and the water leaves the deposit. The body is then cured in an oven. The first electrocoat primers were of the anodic type, but nowadays cathodic electrodeposition has become the standard almost everywhere, combined with the wide-spread use of galvanized sheet metal [12].

Typically, after the electrocoating process, the car body priming is not complete. This layer guarantees protection against the chemical alteration of the sheet metal parts, but usually a powder, solventborne or waterborne primer, sometimes referred as a "filling primer" or "surfacer", is sprayed electrostatically on the surface to guarantee mechanical resistance to stone chipping and further UV and corrosion protection. It also provides an improved base for the support and adhesion of the subsequent paint layers.

This filling primer can be sprayed electrostatically or without charge. Nowadays, the majority of the automakers use electrostatic spraying for fillers, to lower the overspray as much as possible. This is very important for both environmental regulations and paint savings. The car body and the paint are oppositely charged with high voltage, improving the adhesion of the coating to the panels. The coating jet "wraps" the metal parts and the overspray is dramatically reduced. If a particle does not hit the surface, but its kinetic energy is not enough to escape the electric field, it turns in the air and it goes back to the car body. A typical value for an electrostatic spraying process transfer efficiency is 70%-80% (paint that exits the nozzle which goes effectively on the surface). When powder is used, values up to 97% can be reached, but this can only be achieved by overspray collection and recirculation: the transfer efficiency is then not obtained considering just the coating first pass spray process, but it is an overall value, computed considering the final coating waste. This result has the effect of decreasing the costs associated with sludge removal and disposal.

Using the analysis contained in the document "Voltage Block Systems – Technological advancements for Waterborne Electrostatic Painting" [13], the economy of electrostatic spraying is very basic and yet effective; approaching the problem from the flow rate required by the atomizer to achieve the desired film build, if the present method has a 60% transfer efficiency and a flow rate of 300 cm^3/min, and the gun is triggered for one minute, the amount of coating deposited on the surface is

$$300\ cm^3/\min\ \times 1\min \times\ 60\% = 180\ cm^3 \quad (1)$$

Now, consider that the goal is to keep the amount of coating exactly the same, but with a system where the transfer efficiency is 75%. This means that the flow rate out of the nozzle has to be

$$180\ cm^3/75\% = 240\ cm^3/min \quad (2)$$

Computing the paint savings:

$$(300 - 240)/300 = 20\% \quad (3)$$

The result is that with an increase of the 15% in transfer efficiency the saving on paint can mean that the actual saving is more than just 15%, and it explains why investing in electrostatic application or any other technologies that improve the transfer efficiency has been of paramount importance for the painting industry.

Electrostatic spraying can also be problematic, in the case of semi-closed sections or of anything that can work as a Faraday cage: the electric charge density on the internal surface becomes null and – especially with powder paint – the spray adhesion to the surface is very poor. Great care should then be taken in the design phase of the car body and of the painting process. This is a simple example of how integrated design is mandatory for large companies, and of how engineers that design the product nowadays need to have great knowledge of the manufacturing process.

2.1.1.1 Powder:

In the case of powder coating the electrostatic charge is the only way to generate adhesion to the surface, and the powder is first fluidized by compressed air, then another compressed air stream pushes powder out through a nozzle, which can be conical or a bell. At the nozzle, DC current with a high voltage and low current charges the output of the spray guns.

2.1.1.2 Solvent borne and Waterborne:

These two types of coatings differ from powder coat because they are in liquid form. Waterborne paint electrostatic application is challenging, because water is conductive. The charge that is given to the spray at the gun tip, then, tends to move back through the coating into the pump and to the ground. This means that none of the particles that will reach the car body surface will have an electrostatic charge, and the benefits of the electrostatic application vanish. A spray gun for waterborne paint has an isolation block that prevents the coating from “grounding out”. It is substantially easier to charge solvent borne paint electrostatically, but today the gap in performance between the two has been completely filled.

It’s very important to point out that waterborne primers contain less Volatile Organic Compounds – VOCs – than solvent borne ones. Powder has null VOCs emissions, but since the film thickness obtained is usually double that given by the waterborne primer, getting a satisfying uniformity of the surface is more difficult and its curing requires a higher temperature in the oven, leading to higher energy consumption.

VOCs affect human health in several ways; they can cause skin, eye, nose and throat irritation, headaches, dizziness, visual disorders and memory impairment, and many of them are suspected to cause cancers in humans. Their concentration control is then extremely important especially in the case of manned stations, while when dealing with fully automated stations their presence can be tolerated, up to values that still guarantee that the booth VOC concentration is far from the Lower Explosion Limit – LEL. Moreover, there are regulations that limit the VOC emissions in the exhaust in many places in the world, and some companies are self-committed to improve the quality of their emissions. Any exhaust stream that has a high concentration of VOCs must be treated, with a consequence of energy consumption. Numerous strategies have been studied to reduce this impact. A normal system, supplied by companies such as Dürr, can easily achieve the 95% VOC abatement, and since one way of reducing them is to oxidize them – and the oxidation process is exothermal – the heat produced can be used to heat or pre-heat the air flow to the oxidizer. In order to reduce the amount of fresh air to be treated, a typical configuration is the recirculation of 75-85% of the air back to the booths after its conditioning in Air Recirculation Units – ARUs [14].

Curing waterborne coatings presents some difficulties compared to solvent borne: the different evaporative behavior of water and its different physical characteristics can lead to bubbles popping on the coating surface. This effect is usually called “blistering”. It is important to avoid nucleation of the water by maintaining the right temperature inside the oven and avoiding excess humidity in the spray booth [15].

2.1.2 Topcoats

Topcoats have as their main purpose to provide stability to the coating system and to build an aesthetically appealing effect. Metallic or mica-pearlescent ones have a base, colored layer, called basecoat, and a top, transparent layer, called clearcoat. While solid color (“straight shade”) topcoats can be applied in a single layer, nowadays the standard is to have basecoat and clearcoat for any type of finishing. The thickness of the basecoat layer is usually lower than the clearcoat.

2.1.2.1 Solvent Borne Topcoats

Pigments are the components that give color to the paint. Usually the effect is obtained with a uniform dispersion of powder-like crystalline particles that reflect parts of the light spectrum, giving the desired color appearance. The uniform dispersion of these particles is extremely important for an acceptable result. Particle size, distribution and structure influence the color shade and the effect of wetting of the particles by polymer solutions.

Solvents give stability to the resin solution, and they affect the film building process and the viscosity of the paint. They have to be adjusted in order to get the right evaporation rates depending on the application, technology, and oven temperature. An error in the formulation of the paint can lead to poor results and paint film failures that can be immediate or that can happen later in the vehicle life. Their composition can vary depending on the manufacturer's choice. Several types of organic compounds can be used: aromatic hydrocarbons, esthers of alkanols, alcohols, alkanol ethers, and so on. The use of some components has been restricted over the years in Europe and/or in North America.

Traditionally, the metallic basecoats contain Cellulose AcetoButyrate (CAB) with a suspension of aluminum flakes that give the metallic appearance. This material is extremely suitable for this purpose because the topcoat is applied with a very short flash-off time between the basecoat and the clearcoat applications. As in any other type of paint, the basecoat has to be insoluble in the clearcoat without the need of an intermediate curing oven. The CAB is able to wet the aluminum flakes fixing them in the layer. The clearcoat is necessary because the basecoat itself has poor resistance to water and other agents, especially in the case of highly pigmented basecoats with aluminum flakes.

In the case of mica paint, flake shaped particles derived from aluminosilicates are dispersed in the resin, and covering the mica particles with thin layers of heavy metal oxides gives them their particular pearlescent effect: the reflection of the light on the vehicle surface gives the car body different colors depending on the angle of incidence.

2.1.2.2 High-Solids Topcoats

Increasing environmental awareness, starting from the 1970s, cleared the way for investments in eco-sustainability. The Volatile Organic Compounds that derive from solvents in paints began to be perceived as a problem and strategies to clean the exhaust of paint booths started to be developed.

It is possible to catalytically oxidize the solvent vapors, but it is only part of the solution: the physical separation and recycling of the solvent is extremely expensive, due to their very low concentration in a very high air volume. Addressing the problem at its root, the companies started developing “cleaner” paints, with lower solvent contents. Two solutions are high-solids and waterborne topcoats. Conventional solid color topcoats contain 50-60% by weight solvents. Clearcoats are around 60%, while metallic basecoats can contain up to 90%.

The solids content of a topcoat paint can be increased by keeping the molecular weight of the polymers low in order to maintain liquid viscosity. Depending on the formulation of the paint – alkyds, acrylic resins or melamine resins – there are different strategies that can be used. The durability of the paint, however, is usually worsened by shortening the polymers, so more resin-resin bonds are needed. Good performances have been achieved with the use of two component paints, in which the base and the hardener are dispensed separately by the gun. The solids can increase from the 40-50% by weight in conventional paints to more than 60% for high solids topcoats.

To raise the solids content of metallic basecoats, several strategies were studied, such as the substitution of part of the CAB with other resins or the employment of non-aqueous dispersions (NAD). These strategies can raise the solids content up to 20-25%.

High-solids clearcoats are obtained by combining low molecular weight acrylic resins with abducts of polyisocyanates, and the product obtained guarantees more than 60% in solids content and a perfect compatibility with waterborne basecoats.

2.1.2.3 Waterborne Topcoats

High solids coatings show that the degrading of film properties limits the increase in solids content, and to overcome this limitation, water can be used in paint preparations. Water is very difficult to deal with when used as paint base, because of its high boiling point, energy and time of vaporization, high density and surface tension. The major problem is that the polymers have to be modified to be used with water as a solvent or dispersion agent.

Water presents a challenge for its compatibility with the aluminum flakes. They have to be stabilized with special surfactants and coatings in order to be used in a water-based paint. Waterborne basecoats can have a co-solvent that helps water in its duty as dispersion agent, but they still contain less VOCs than the high-solids basecoats.

The main difficulty in this case is the evaporation of the water out of a rather thick paint film and its consequent stability. While usually the environmental sustainability of high solids solid color topcoats is considered acceptable, double layer waterborne solid color topcoats have been developed. In this latter case the solid color basecoat is developed with the same resins as the metallic one, with the challenge of achieving good hiding power in a thinner, aqueous film.

It is very difficult to employ waterborne clearcoats, because of their inferior applicability, gloss and durability properties compared to the solvent-borne type. It is unusual to find waterborne clearcoats, while some attempts have been made to use powder and slurry clearcoats.

2.2 Technological Challenges

The paint shop is an area in which there have been major investments for improving the performances in terms of the energy and environmental impact. Even if a lot has been achieved in the past 40 years, the engineers have to deal with new technical challenges due to the increasing environmental awareness and regulations.

One of the most important and toughest challenges of today is the lifecycle approach to the manufacturing process, intended as an integrated approach between product and process, taking into account raw materials, their production or extraction and all other environmental considerations. Prendi et al. [16] analyzed the paint process under this “new” light. They investigated the use of waterborne coatings, which are nowadays preferred to the solvent borne because of their lower VOCs. Their study weighed factors that are typical of LifeCycle Analysis – LCA – such as the production process of the paint itself and the process variables in the paint process. It is a complex matter, and the parameters to take into account are many and some of them not easy to quantify. They concluded that, in reality, waterborne coatings are comparable to the solvent borne ones, considering their lifecycle and their impact on the car painting process.

A greatly unexplored topic is the recycle of the exhaust flow enthalpy. It is the same concept as a vehicle's turbocharging, in which the enthalpy contained in the exhaust is recovered to power the compressor at the engine inlet. Roelant et al. [8] created a model of a generic paint shop, predicting the energy consumption, operation cost and environmental impact of the manufacturing process. The environmental analysis was extremely refined and showed the same LCA approach of Prendi et al. [16]. They then identified a possible source of savings in utilizing the enthalpy of the exhaust of the RTO oxidizer to heat the process air for the spray booths. Their model was able to predict that the energy recovered is enough for the air treatment requirement, leading to a significant saving in fuel. They then suggested a heat exchanger network to effectively implement the solution in real plants, taking into account payback, environmental impact of their production and operating costs, to find an optimum for the design. The scheme in Figure 2.2 describes their idea of recovering exhaust enthalpy.

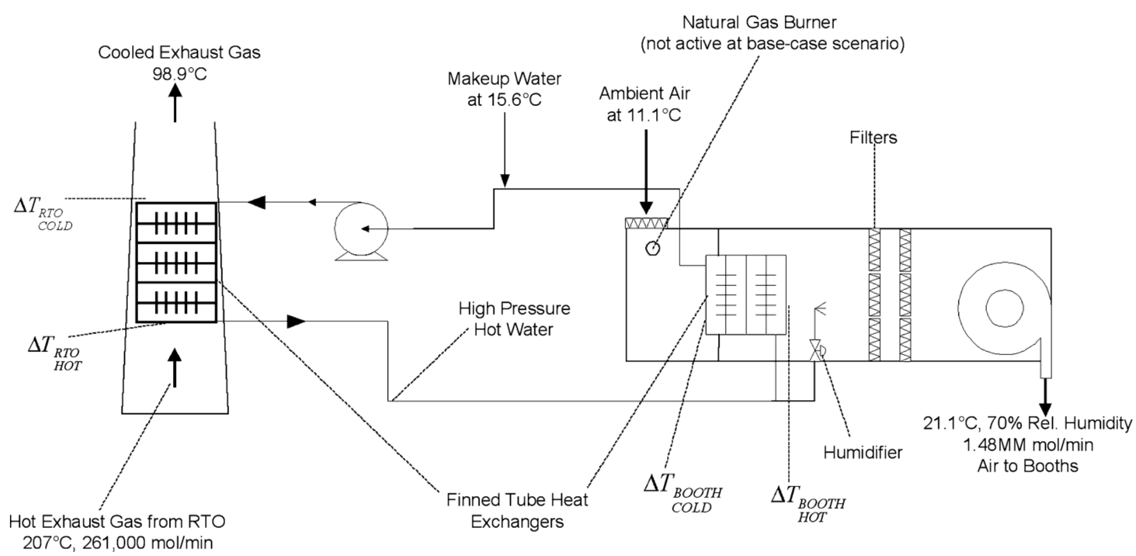

Figure 2.2 – System to recovery paint shop exhaust enthalpy [8]

Dürr director Enregaard showed the trends in the automotive paint application technologies [6], highlighting the challenges that are possible to be overcome with new robots, new layouts and new methods for electrostatic application. One of the main targets of the actual automotive industry is the improvement of the transfer efficiency of the electrostatic powder application, that nowadays can reach 95%. The goal is to get as close as possible to 100% without significant cost increases. Another target for the paint booths is to automatize 100% of the operations, using highly flexible robots and cost effective strategies. New paint booths are close to this objective – and sometimes they have already achieved 100% automation – thanks to highly specialized anthropomorphic robots that are able to paint the interior and difficult spots without human intervention. A – minimal – manned station can still be present though, for details and hidden spots.

Another way to dramatically reduce energy consumption is to make whole processes become unnecessary and consequently eliminate them: an example is the wet-on-wet coating deposition, in which the coating is not cured in between the application of two layers, thanks to special coating formulations and dehydrating processes. This results in the elimination of an oven and, as a consequence, in a big energetic improvement. Today, companies try when possible to make the painting process as lean as it can be, focusing on complying with high quality and productivity standards.

2.3 Energy in Paint Shops

The word “energy”, when used in a context like a manufacturing or assembly plant, is a simple term to describe a complex mix of energy carriers. These carriers can be natural gas, hot or cold water, electricity, and (dealing with industrial facilities) compressed air. An energy carrier is a substance or a phenomenon that carries the potential for doing work when used with the proper equipment. It does not create energy, it transports it. A well-known energy carrier is the electric battery.

So, when analyzing the energy involvement in a manufacturing/assembly/paint process it is important to target the study to the analysis of the different carriers; typically, energy is purchased by companies as electricity, natural gas and hot/cold water, which are fed to the production processes in the forms of:

- Electricity
- Hot water, that can be:
  - Heated on site with natural gas
  - Supplied by the utilities company
- Hot steam
  - Created with natural gas
- Compressed air
  - Usually compressed on site by a centralized compressor powered by electricity

But the unit cost, normalized to the actual energy usable content, of the various carriers is different and varies depending on the location and on the utility company. In North America, every province or state has its own average rates, and Michigan electricity or natural gas costs are very different from Ontario ones. Moreover, where there is a big gap between natural gas and electricity cost – typical of some European countries or locations with scarcity of natural resources – this gap can affect the plant choices in terms of energy purchase or self-production. In Italy, it is not rare to find a power plant in a manufacturing facility: Fiat Mirafiori plant, in Torino, has a thermal-electric power station that supplies the whole complex. The cost of natural gas compared to the direct purchase of hot water from the utilities company can also determine whether the hot water will be produced on site or bought from the provider. Since the purpose of an energy model is usually the analysis and/or optimization of costs, all of these variables should be taken into account in the model.

2.3.1 Users & Sinks

With the purpose of creating a model of a paint process, one of the first phases of the process is to analyze for what the energy is actually used. Motors are the main electricity consumer in a vehicle assembly plant, because they are employed in a variety of systems: fans, pumps, robots, conveyors and lights.

Fans are the most ubiquitous equipment along the paint process. They are essential to guarantee the workers' health, to ensure optimal quality levels to every paint layer, to respect the air temperature set points, to ensure good air circulation in ovens and flash off booths, and contribute to the optimal heat transfer between the hot air and the painted body. Air flows are crucial and not easy to design, and an audit with consequent tuning to align the actual flow to the design value is usually needed.

Pumps are almost in every station of a paint shop, and they're used to feed chemicals and/or water to the manned or robotic station, to circulate the paint in the tanks, to feed the powder to the powder guns, to send the paint to the spray guns, and to circulate coolant or hot water in the heat exchangers. A pump's efficiency usually is around 65-75%, and its behavior is much more predictable than for fans.

In some plants, robots have become the main tool for painting a car: they can apply sealant, prime the surface, spray the interior and the exterior, move parts and rinse the body. Manned stations in high-output and highly-automated plants are usually reduced to an essential finishing stage and quality check booths, in which workers compensate for the not-yet-full flexibility of the robots. Motors are used to move the parts around different axes of the robots, and usually each joint has a built-in electric motor: Obviously, the bigger the distance from the joint to the end effector, the bigger the inertia and the larger the energy required for the payload motion. Energy efficient programming of robot kinematics implies that the largest motions will be carried out by the closest motor to the end effector.

Conveyors are the core of modern industrial processes. They're responsible for the logistic flows inside plants and they move the car body throughout the whole manufacturing process. In a paint shop, conveyors and handling equipment are able to move, rotate and occasionally – as will be discussed in the subsequent sections – tilt the car body, so that it is able to enter every single station and be processed in it. In the data of Figure 1.1, that refer to a whole manufacturing plant and not just to the paint shop, the electricity load of the conveyors falls into Material Handling and it cannot be neglected when looking at the overall picture.

Natural gas or any other fuel is used to heat the cold flows that interact with some of the processes. In the pre-treatment and e-coat phases, fuel can be used to maintain the temperature in the dip tank baths, while in the ovens it is used by burners to heat up the air flow. In the booths it plays an important role in the conditioning of the air, when the air needs to be re-heated after de-humidification or in the case of low winter external temperatures.

Hot water can be used directly in the heat exchangers as an alternative to heat cold water with a fuelled burner. As already discussed, the choice is made according to the energy carrier cost and the overall efficiency of each method.

Compressed air is another very important carrier in every manufacturing plant. In a paint shop it is used to power some of the pumps, to move pieces of equipment and it has a fundamental role in the powder pumping equipment: a compressed air flow "pushes" the fluidized powder in the duct to the atomizer and a secondary compressed air jet atomizes the powder and disperses it in the air flow towards the car body. In the color booths, the compressed air plays a similar role in paint atomization and spray.

2.4 Modelling a Paint Shop

The development of simulation and modelling techniques, as well as the great availability of tools in the market, has contributed to the diffusion of what has become a revolution in the process/manufacturing engineering world. Moreover, the increasing awareness of the paint process role, in terms of perceived quality and of lifecycle impact on the final product, has brought some attention to the importance of the simulation and modeling of this part of the car manufacturing process.

To model industrial processes, it is usual to employ software and methodologies of Discrete Events Simulation (DES), in which every single event produces a modification of the state of a station. In between the events, nothing is observable in the whole system, and it is "frozen". This methodology is in contrast with Continuous Simulation, in which the simulation continuously tracks the dynamics of the system over time [17].

These approaches are extremely suitable for the analysis of a manufacturing system in terms of productivity, system variables, efficiency, asset utilization, and to have a generic idea of the energy involvement in the whole process. For a more specific energy analysis, with detailed resource utilization and the ability to use the simulation to predict different scenarios' economic impact or foresee the effect of a major change in the manufacturing process, a different approach is required. Depending on the main goal of the model, the operation can be performed in a specific way. In the following, some examples of different methodologies are reported, targeted to their aim.

Arinez et al. [18] studied improvements in an automotive paint shop in terms of throughput. They considered the paint process as a Quality-Quantity Coupled operation, with nonperfect quality machines. Their approach was at first statistic, and they identify the throughput (TP) function to be dependent on the probability (p) to complete the job during a cycle time. Specifically, TP is a concave function of p. It is of interest to report their modeling approach, based on the work of Li and Meerkov [19]. It consists of four phases:

- Layout modeling, i.e. the investigation of topological arrangements of the operations.
- Structural modeling, i.e. the reduction of the layout to a standard analytically analyzable model, as is shown in Figure 2.3.
- Parameter identification, i.e. the evaluation of productivity and quality parameters linked to the operations and to the buffers' capacities.
- Model validation

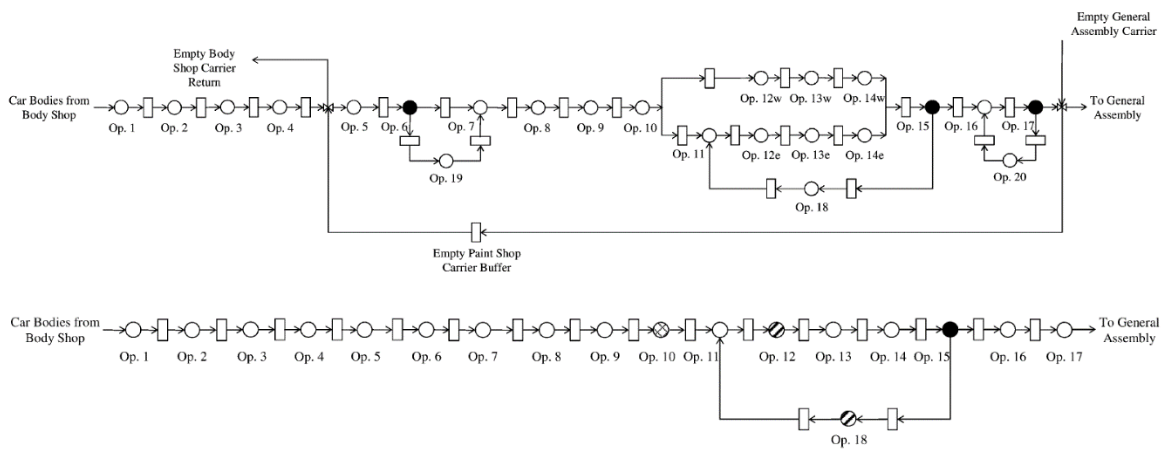

Figure 2.3 - Layout (Top) and Structural Model (Bottom) of the [20] paint process

It is possible to define this as a probabilistic model, and the authors are able to find quality-quantity defective operations and suggest basic improvements that would raise the TP by more than 10% of the original value. Arinez et al.'s model [18] is then suitable for throughput and productivity analysis, but its lumped representation of the various stations and the absence of any links with process variables such as temperatures, flows or physical dimensions make it not appropriate for the energy analysis in the scope of this work.

It is clear that the type of investigation for which the model is employed plays an important role in determining the form of simulation and the characteristics of the model itself. It is useless to waste time and resources on a complete model if it can be reduced to a partial one that gets to the same target. Adding useless complexity is a choice that has to be balanced against resources when dealing with simulations of industrial processes.

The closest model to the scope of this work is the result of the work of Jlenia Puma [7], who has been part of a project that has produced a tool for energy estimation of a paint shop. It is an analytical model, based on several Microsoft Excel® documents and worksheets, with a user interface. A library of various FCA plants in the world is available for selection and it is possible to configure the process targets/variables to predict the effect of changes on the process. Weather average data are used to estimate the load on the HVAC system as well as on the air treatment units of the various booths and ovens. The energy required for the thermal management of the dip baths is computed with a convective-conductive analysis, considering the heat capacity of the car body and its carrier.

Since it was in the aim of Puma's model [7] to be as modular and user friendly as possible, and be able to be used for different plants and with moderate variability of the process, the complexity of the tool is extremely high. It also takes into account building HVAC that is out of the scope of this work. Puma's model will in that case be used as reference for the results of this thesis, and some parts will be directly implemented, such as the computation of the energy consumption of the booth ATUs, since it would be worthless to re-think something that has already been done and realized without requiring any major changes and/or improvements.

The aim of this thesis is then to produce a model that can predict the energy consumption of Sterling Heights Assembly Plant paint shop, with sufficient accuracy, and whose parameters can be set and modified according to different case scenarios.

3 Methodology

3.1 Introduction

The structure of the model has been heavily affected by the goals of the project, which tries to satisfy the needs of both the industrial and the academic worlds, these can be summarized as:

- obtaining a model that can theoretically estimate energy consumption of an industrial process, which can be very important for companies that need more and more tools to support their strategic decisions in such a dynamic market, such as being able to:
  - evaluate the impact of a change in a system;
  - evaluate the impact of a change in the way the system is managed;
  - guarantee reliable results;
- generating an actual picture of the current solutions employed in the process, which can be convenient for a more straightforward approach, and which is able to:
  - summarize the whole process technical data;
  - be directly used for some estimations.

The idea behind this project is then to develop a tool that performs these two operations, in an integrated way. A theoretical model can be fed by the data retrieved from the plant, in which there would be a precise and complete picture of the process. Unfortunately, to reach this goal some limitations and difficulties may have to be overcome:

- the large quantity of data that needs to be collected and organized to produce a "snapshot" of a whole process. An average paint shop consists of numerous pumps, fans, heat exchangers, tanks and much more, and each piece of equipment usually has a motor, and can interact with one or multiple flows. To collect and organize such a large quantity of information in a concise way is therefore one of the many difficulties that has been encountered in the development of this project;
- the limited availability of the information that is needed for the completion of this kind of project. Especially in the case of old plants, it can happen that the majority of the data can be retrieved only by physically accessing the production site, and the actual production line. This latter scenario can make information collection impossible, or

limited to scheduled down times. Modern plants are usually equipped with several systems that can monitor the real time state of the various parts of a process, and have up-to-date documentation that can be used to get all the information about each piece of equipment involved in the process. Walking physically along the process is still generally required to check that all the data are correct and to acquire some details that are not retrievable from drawings and documentation, such as the temperature of a wall or the actual plant routines;

- the intrinsic amount of work required to collect, organize and use all the information, can make such a project enormously inefficient and not feasible: the plant is subjected to changes in time, and it is quite possible once the work has been completed the actual situation could be different from the "virtual" one.

In this chapter the methodology used to overcome these problems, as well as the actual model structure will be explained in detail. The modelling procedure has been divided in:

- first phase: data collection;
- second phase: initial computations;
- third phase: calibration;
- fourth phase: run alternative scenarios.

The plant that has been chosen for the project is the FCA Sterling Heights Assembly Plant, often abbreviated as SHAP, in Sterling Heights, Michigan, United States. It produces the Chrysler 200, and all the operations that will be described in the following have been done with the SHAP as the reference and subject of the work.

3.2 The Calendar

One of the unique elements of this model is MS Excel® worksheet, which contains a calendar year, in which the user can set and manage the production shifts, vacations, and down time in a whole year. A day has 3 adjustable shifts – in another sheet, called model variables, the user can set the time in which the shifts start and end – and production is color coded for easier readability. A shift in which the production is normal appears orange, one in which assets are shut down is yellow, and down time with no shut down is white. The user can click on checkbox buttons on the side of the calendar to use preset schedules, or can manually populate each shift of the year, for a more customized setting.

Although MS Excel® does not have a function that returns the background color index of a cell, user defined functions (UDF) can be used. A function named BGColor() has been coded using Visual Basic® and integrated in the workbook. In this way, the color inputs by the users can be converted into indices that can be managed by MS Excel®.

In the Model Variables sheet, moreover, the user can set which asset to shut down during weekends or vacations, using checkbox buttons. Using a slider it is possible to select the throughput in terms of jobs per hour (JPH), according to the plant production schedule, varying between 1 and a maximum that has been set according to the capacity of the SHAP plant, and that is not modifiable by the user.

The outcome of the calendar module is a spreadsheet in which each row corresponds to an hour of a specific day along the year, and each column corresponds to a system in a phase of the process. For each of them a “1” is written if that system is working at that time of that day, and a “0” is inserted if that system is shut down. Additional columns regulate the start-up transient behavior for the systems with significant inertia.

In Figure 3.1, a screenshot of an example of the calendar module operation is shown. The yellow cells refer to the shutdown of the process during vacation, and during the year the production is organized in two shifts, with the systems still operative in the third one and on the weekends.

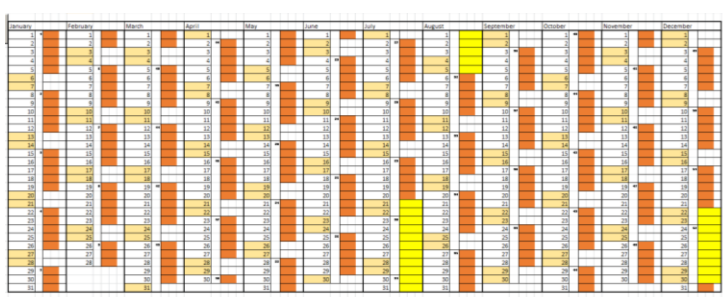

Figure 3.1 – Example of calendar

In Figure 3.2 a detail of the calendar module and a part of the panel that allows the user to select which asset to shut down during downtime is shown. The user acts on ActiveX buttons, and the cells background color changes depending on the selection.

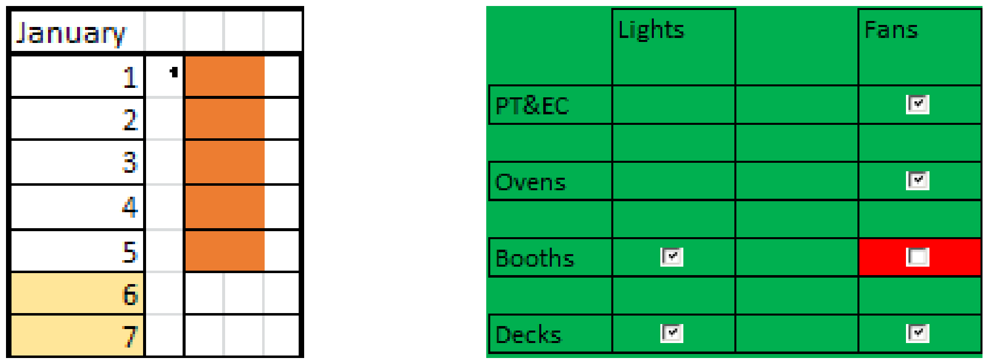

Figure 3.2 – Detail of the calendar module and part of the shutdown selection panel

3.3 The Weather

Some processes of the paint shop interact with the external environment, directly drawing fresh air from it. It is important then to consider the outside air conditions, in terms of dry bulb temperature and relative humidity, by making reference to a table of the average values for a typical year. We can identify two major fluctuations: the seasonal fluctuation with an annual frequency, and the one generated by the day/night cycle. It is important to remark that this model assumes that ovens and booths draw air directly from the outside and not through a cascade from the plant. This choice has been made because the estimation of the consumption of building HVAC – that usually would carry part of the load of heating and conditioning the air for booths and ovens – is not in the scope of this work.

Therefore, the weather module for this project has to give information about temperature and humidity at different times during the day, averaged throughout a month. EnergyPlus® weather data have been found to be extremely suitable for this purpose, and have been directly implemented in the model [20].

3.4 The Models

To efficiently address the objective, this model has been developed as two parallel paths, one that refers to the real data of the plant and that provides a total energy consumption based on monitored energy consumptions of individual pieces of equipment, whose operations are simulated in a virtual environment, and the other one that models the process from basic principles and can be used to understand how the energy consumption would change in the case of modifications of the current situation (the analytical model). In Figure 3.3 the first path is on the left hand side, while the analytical model is on the right hand side.

As shown in Figure 3.3, the operation of the left hand side is fed by the data of the pieces of equipment that are involved in the process. Some computations are performed, based on some assumptions that are also inputs for the model on the right hand side, and as a result an overall energy consumption value is obtained. This value can be trusted if the equipment data are reliable and the assumptions used don't affect the result by a large extent and are used in the same way as they are in the model on the right hand side.

The model on the right hand side was calibrated on the basis of the results of the left hand side computations and by comparing the outcome with the values that are present in the literature [4], [5], [6]. This operation is represented in Figure 3.3 by the orange curved arrow. Then, the user can manipulate the process parameters in the right hand side and calculate the energy consumption of the paint shop.

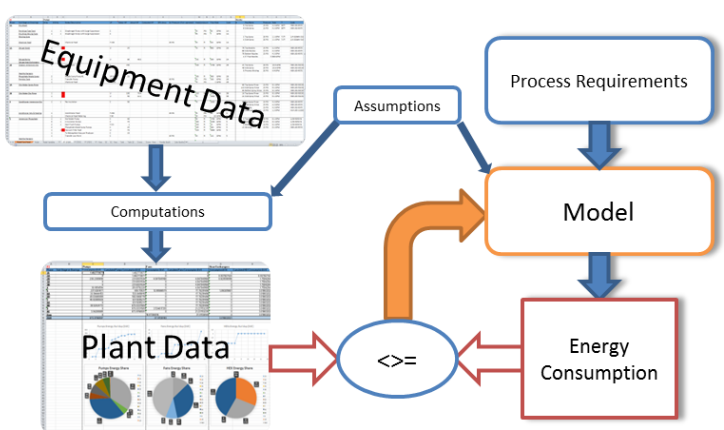

Figure 3.3 –Representation of models used in this thesis

The model consists of several sub-models that for sake of simplicity, have been coded once and that are fed by the process requirements of each section. The fundamental blocks in Figure 3.4, dip processes, booths, and decks and ovens, are analytical models in which convection and conduction analysis, thermal flow balances and lighting computations are performed.

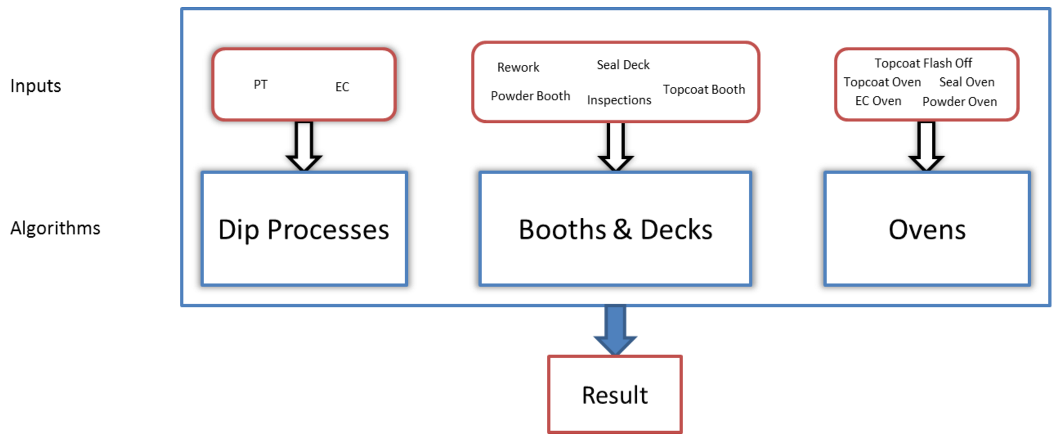

Figure 3.4 – Fundamental blocks contained in the model

The components that have been modeled for each one of the process types are shown in Table 3.1. A check means that that element has been modeled, while a circle means that that element has been added to the sub-model as a constant. For the booths, air treatment has not been modeled, as already discussed in the previous sections, and the computation has been done by an external tool provided by FCA. The pump power for the dip processes has been added from the results of the computations on the left hand side of Figure 3.3, because of its constant characteristic and of the difficulties found in linking it to the process requirements.

Table 3.1 – Modeled components in each of the sub-processes

	Dip processes	Booths and Decks	Ovens
Convection	✓	-	✓
Fan power	✓	✓	✓
Pump power	○	-	-
Air heating	-	-	✓
Air treatment	-	○	-
Lighting	-	✓	-

3.5 First phase

The data collection, which coincides with the input generation for the model, was the first operation that was performed, and the most important one. In approximately two months, all the necessary information was collected, checked and organized in a MS Excel® set of spreadsheets that are so organized:

- Each sub-process has been given of a set of worksheets, in which a dedicated interface has been created for the input operation. The various sub-processes have been selected according to their organization in the SHAP documentation library, and are:
    - pre-treatment or phosphating
    - e-coat
    - ovens
    - powder booth
    - color booths
    - decks and booths.
- Each sub-process has been organized in several worksheets, named steps, some of them open for the user to modify. These sheets are:
    - STEP 1, in which the user inputs the data of the equipment that is employed in the process. Instead of creating a mask, the user acts directly on the fields that are unlocked in the sheet, and is guided by an interface and color coded error warnings.

      There are six fundamental categories of equipment that can be inserted by the user: fans, pumps, heat exchangers, tanks, burners and air treatment units. Each piece of equipment that is put into the system is required to have a utilization factor, which acts as a correcting parameter for the elements whose use is not continuous, and a code that corresponds to its tag at SHAP. The input data for each category are:
        - fans and pumps: code, Utilization Factor (UF), motor HP, design power, actual power, Δp or head, design and actual flow rate. Pump Δp can be inserted as pressure in PSI, Pascal, or as head in feet. Power information is required to be in horsepower.

        - tanks: tag code, physical dimensions, fluid type and temperature, wall material and thickness, insulation material and thickness, tag codes of the pumps used for recirculation of the fluid
        - heat exchangers: code, type, in and out cold fluid temperature and rate in operating conditions, in and out hot fluid temperature and rate in operating conditions, rating, hot and cold fluid temperatures and rates in bring-up conditions
        - burners: code, zone, type, fresh air flow, total air flow, outlet temperature set point, recirculation air temperature, supply fan characteristics
        - air treatment units (ATU): code, zone, fresh air intake, set point temperature, set point humidity, cascade and recirculation air intake, rating
    - STEP 2, invisible for the users, in which the information from STEP 1 is transformed into SI units, then checked and elaborated for the subsequent step. In some cases the user can insert values in different units – such as pressures in PSI or inches of water column – and the algorithms in STEP 2 separate the value from the units, read the units and apply the right conversion factor to bring everything in metric units
    - STEP 3, accessible by the user in read-only mode, in which diagrams and charts show the results for that specific sub-process
    - STEP 4, only for the sub-processes in which dip tanks are used, manages the information of the dip tanks separately from the rest of the equipment, and merges the information on the heat exchangers that are inserted by the user with a heat transfer estimation resulting from a convective analysis performed on the basis of the data in STEP 1
- Each STEP sheet is divided by rows into the several sections that make up the sub-process, in a logical process order, following the path of the Work In Progress – WIP. This allows the user to analyze the energy impact of every station along the whole process.

- In the STEP 1 worksheets the only interaction with the user is through a warning cell that is highlighted when the inserted data are wrong or incomplete. In the STEP 2 worksheets some checks are performed:
    - completeness checks, in which the algorithms check if there is all the information to compute the energy consumption of each piece of equipment, and whether the data inserted are the most direct and complete ones. Taking a fan as an example, if the code detects that the only information about it is the power of the motor, it automatically computes the average ratio between motor horsepower and actual fluid power of all the other fans and applies the same ratio. Or, if the code detects that the user inserted a flow rate and pressure drop, it uses these values to refine its computation. If the code doesn't have any information about the power of the fan and flow data are missing, then it sends a warning message to the STEP 1 sheet, highlighting the corresponding cell.
    - quality checks, in which the algorithm checks for values that are off of the average by 10 times: this choice has been made because of the nature of the input operation, in which it is likely to make a mistake and input a value that is one or more orders of magnitude higher or lower.

In the STEP 2 sheets, the information is collected and converted in SI units. Then, some assumptions are applied, and for each piece of equipment a final power consumption value is computed. These values are then summed up and managed by the calendar module, to obtain the overall consumption of every section of the paint shop.

3.5.1 Assumptions

It is not feasible to entirely model the real world in its complexity, and sometimes it is important to simplify the problem using the right assumptions. In this project the assumptions that have been made for the left hand side of Figure 3.3 are also used on the analytical model (right hand side) to avoid errors, and have been summarized in the following.

- Utilization Factor (UF) is a correction factor that accounts for the intermittent use of some pieces of equipment, and was directly multiplied with the computed consumption of each element. It is assumed to be 1 in the case of continuous use, 0.6 for equipment whose use depends on production and 0.1 for equipment that is used for less than an hour during each shift. Moreover, if the user knows that a pump is used to feed a tank, it is possible to use the tank dimension and flow rate to calculate a utilization factor.
- The heat transfer in the dip processes of phosphating and e-coat was assumed to be limited to evaporation heat transfer, heat exchange with the car body, kinetic energy from circulation pumps, and convection through sides, inclines, and roof, while the convection through the bottom and radiation heat transfer were neglected.
- The temperature of the dip bath was assumed to drop by 5.5°C after 48 hours of inactivity (e.g. after the weekend).
- The car body was assumed to not heat up to the bath temperature for its whole mass. This accounts for the fact that the car body doesn't exit the dip tank at the same temperature as the bulk fluid, but there is a temperature gradient going from the surface of the car metal, which is at the same temperature as the bath, to the core of the car body panels. The fraction of the body that reached bath temperature was initially chosen to be around 30% considering previous works [7], and then it has been adjusted in the calibration phase.
- The lighting along the whole length of the pretreatment was considered nonexistent.
- The circulation pumps were assumed to work continuously, and could not be shut down during the weekend. Especially in the case of e-coat, without the continuous action of the agitator pumps the solid particles in the fluid would coagulate and the bath would need to be renewed.

- For the computation of the heat transfer coefficients, the external wall temperature of the dip tanks was assumed to be 5°C higher than the ambient temperature inside the plant, and the external wall temperature of the ovens to be 80°C. It was subsequently shown in the sensitivity analysis (Section 4.4) that these values don't affect the heat transfer by a considerable amount, because of the predominance of the insulation layer thermal resistance.
- The air infiltration through the oven air seals was assumed to be equal to the design value, because of the difficulty of measuring this value. This assumption affects considerably the computation of the heat loss of the ovens, being comparable to the convection heat transfer through the walls. Relative to the final result, instead, it is a low source of uncertainty due to the large quantity of energy required to heat up the fresh air and the heat transfer with the car body.
- The ovens' exhaust was assumed to not draw air flow directly from the intake flow, the intake air is assumed to remain in the oven for a whole air change cycle.
- The car body was assumed to exit the ovens at the temperature of the air inside the furnaces, because of the long baking time – around half an hour.
- Heat transfer through booth walls was assumed to be null because of the similarity of the booth temperature and plant air temperature.

3.6 Second phase

Each of the three sub-models in Figure 3.4 is a set of equations that determine heat transfer and power consumption by devices such as fans, pumps and lights. In this section the general principles that govern these equations will be explained.

3.6.1 Dip Processes

A dip process is a section of the paint shop in which the car body is dipped into a bath, which can contain water, a cleaning solution, or a specific coating. Generally, in a paint shop the dip processes are confined to pretreatment, with some dip tanks in the phosphating phase and a main dip tank during the e-coat phase. If a dip process has the purpose of cleaning the car body surface, it is employed to reach the areas that cannot usually be cleaned easily in the spray processes. A dip cleaning, however, can be ineffective in the case of debris and weld balls that have neutral buoyancy, and a spray rinse is usually required.

The bath of a dip process can be at ambient temperature or heated up. In the case of ambient temperature fluid, no energy is required to keep the operations going, except for conveyors, which are out of the scope of this project, and fans. When the bath has to be heated up and kept at a constant temperature, the power consumption of the process can be estimated using a model of the thermal exchanges. In the following, this last case will be investigated. As depicted in Figure 3.5, the tank can be modeled as a box with incoming and outgoing thermal flows, which balance out in steady state.

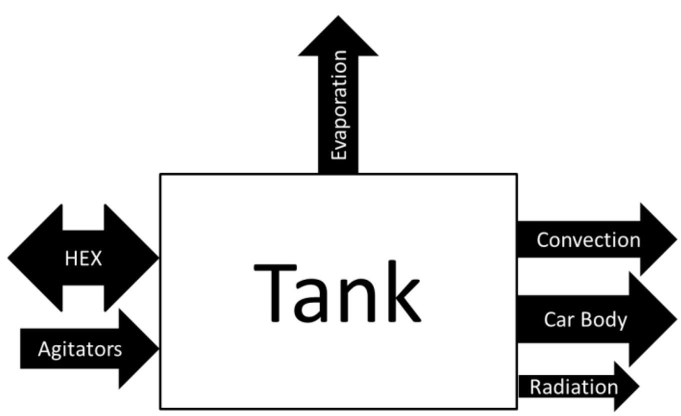

Figure 3.5 – Dip tanks heat transfer schematics

The only flow that is directly regulated by the operator is the heat exchanger's positive or negative heat flux. Depending on whether the temperature of the bath tends to increase or decrease, the heat exchangers that have to keep it constant can be either used to cool down the bath or to heat it up. The only other positive flow is the heat that comes from the agitator pumps. The increase of kinetic energy due to the action of these pumps ends in an increase of the internal energy of the bath, according to the first law of thermodynamics: the work done on the fluid increases the kinetic energy of the fluid up to the point in which the system is in a mechanical steady condition. When the system reaches that point, the work that is given to the fluid by the pumps is exactly equal to the work of the viscous forces, and the bath temperature increases.

Due to the fluid's higher-than-ambient temperature, without any external work done on the system, the net heat transfer between the bath and environment is negative, with the fluid decreasing its temperature. If the circulation pump's work is lower than the heat loss, the heat exchangers will be used to add thermal power to the system. If the circulation pumps work is higher than the heat loss, as in the e-coat tank, the heat exchangers will be used to cool down the bath. In the unlikely case in which the energy added to the system by the agitator pumps is exactly equal to the total heat loss, no heat exchange would be required.

3.6.1.1 Steady-state conditions

In steady state conditions, the heat loss out of the tank can be summarized as:

- convection through sides, inclines and top;
- radiation, neglected due to the low emissivity of the water surface and the low difference in temperature between the water and walls;
- latent heat of evaporation;
- car body heat pickup.

A scheme that represents the operations of the dip tank model is showed in Figure 3.6. The heat flows are the same as Figure 3.5, but the data inputs to the system are the process requirements, such as bath temperature, throughput, tank materials, and water flow rates and temperature, and the output is the energy consumption of the process.

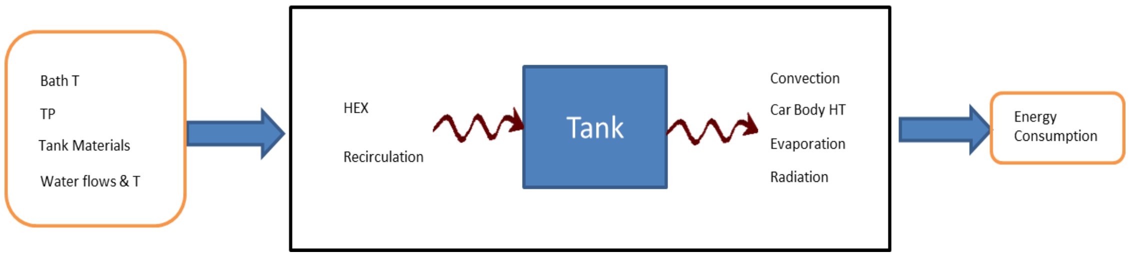

Figure 3.6 – Dip tank model representation, with blue arrows representing the information flow and red arrows representing the heat flow

The convection heat transfer analysis has been split according to the characteristics of the surfaces and of the fluids. In general, heat transfer can be expressed using the equation:

$$\dot{Q}_{overall} = UA\Delta T \tag{4}$$

in which $\dot{Q}_{overall}$ is the heat transfer through a surface (W), with surface area A (m^2), between the temperatures T and $T + \Delta T$ (K). All of these values were known, except for the heat transfer coefficient U. The purpose of a convection analysis was therefore to compute the value of U. A very important concept is the analogy between thermal and electrical resistances. Considering the interface between the inside of the tank and the environment as a composition of three thermal resistances, which sum up to an overall value, as if they were electric resistors in series. In Figure 3.7, h_i represents the convective heat loss coefficient of the fluid inside the tank, k the thermal conductivity of the tank walls and insulation, t the wall thickness, and h_o the convective heat loss coefficient of the air outside the tank. The same concept can be applied at more detailed level, to find k as the result of the composition of the layers of steel and insulation that make up the tank walls.

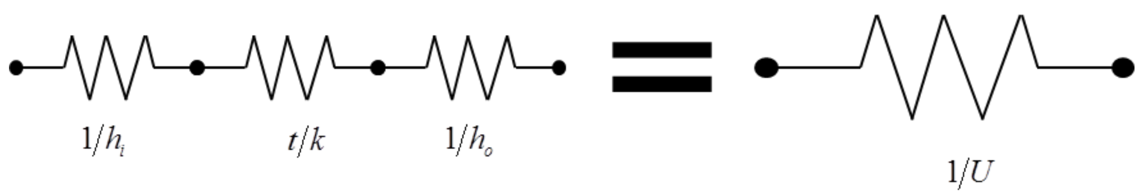

Figure 3.7 – Thermal/electric resistance analogy

The k/t factor, which takes into account the whole wall, with insulation and steel, is then:

$$k/t = [t_{steel}/k_{steel} + t_{insulant}/k_{insulant}]^{-1} \tag{5}.$$

h_i and h_o require a more complex estimation. On the outside and inside surfaces of the tanks convection occurs, and the heat transfer does not depend just on the material properties, but it is strongly influenced by the flow characteristics. Empirical relations between the heat transfer and the fluid properties and motion were needed. Geometrical characteristics as well as orientation of the surface and of the flow have a large impact on the heat transfer, therefore outside and inside heat transfer coefficients have been computed for each of the following surfaces:

- sides;
- inclines;
- water top surface.

The convection through the bottom has been conveniently neglected, because of the thickness of the material and the unfavorable orientation of the surface that does not promote heat transfer. In the following, for sake of simplicity, the fluid contained in the dip tank will be addressed as “water”, although it could be coating or any other type of liquid.

The aim of this part of the model is to compute the thermal load on the heat exchangers, by calculating the heat losses. All the computations in the following are based on the convection heat transfer chapters of Cengel’s “Heat Transfer: a Practical Approach” [21].

3.6.1.1.1 Sides

The air side heat transfer mechanism is natural convection. For this reason, the tank side has been treated as a vertical plate, surrounded by air at a constant, uniform temperature. The natural convection heat transfer coefficient can be computed using the relations for Rayleigh number, obtaining then the Nusselt number, which is the nondimensionalized heat transfer coefficient, as in Equations 6 and 7 [21].

$$Ra_L = \frac{g\beta\left(T_\infty - T_{w_o}\right)L_c^{\,3}}{\nu^2} \cdot \mathrm{Pr} \tag{6}$$

where β is the coefficient of volume expansion (1/K), T_∞ is the undisturbed air temperature (K), T_{w_o} is the temperature of the outside wall surface (K), L_c is the characteristic length (m) and ν is the kinematic viscosity or momentum diffusivity (m^2/s).

$$Nu = 0.1Ra_L^{1/3} \tag{7}$$

The Prandtl number, Pr in Equation 6, is a nondimensional coefficient that is also a property of the fluid, which means that it does not depend on the flow characteristics. The equation to relate Nusselt number to the heat transfer coefficient is:

$$h = Nu \cdot k/L_c \tag{8}$$

The water side heat transfer occurs by forced convection, since the fluid in every tank is kept in motion by agitator pumps. The previous equations could not then be used. It is possible to assume the flow to be turbulent across the whole length of the tank, and again to treat the side wall as a flat plate. The Nusselt number can be estimated with [21]:

$$Nu = 0.037Re^{0.8}Pr^{0.33} \tag{9}$$

Then, using Equation 8 it is possible to obtain h_i. At this point, all the heat transfer coefficients for the sides have been computed. It is important to report that the shorter dimension of the side panels, the height, was chosen as the characteristic length L_c (m).

3.6.1.1.2 Inclines

The two inclined surfaces whose purpose is to facilitate the entering and exiting of the car body in the dip tank have been considered as inclined plates, and all the considerations of the previous section are still valid. The position of the dip tank at the SHAP is such that the inclines are exposed directly to the air, and this facilitated the computations. The waterside fluid motion was assumed to be turbulent and the mechanism for the airside heat transfer was natural convection. The equation used for the waterside is Equation 9.

For the airside, since the air motion depends exclusively on buoyancy, the inclination of the surface affects the heat transfer. Equation 6 has been used, but multiplying the acceleration of gravity by the cosine of the inclination angle from the vertical [21].

3.6.1.1.3 Top

The dip tanks' water level is never close to the top panel. The heat transfer from the top of the bath, then, occurs via the air that circulates above the surface, instead of the plant air. Moreover, the air is pumped inside the dip tank air space by intake fans and withdrawn from it by exhaust fans. Therefore, the air that is on top of the water surface can be considered to be in turbulent motion. The heat transfer occurs only if the air that is blown in the dip tank environment is at a different temperature than the surface of the bath. If this does not happen, there will be no heat leaving the bath, but the heat transfer occurs exclusively between the air flow and the water, through the water surface.

The waterside coefficient was again computed using Equation 10, with the width of the tank as the characteristic length. Since the air motion is turbulent, and assuming the air velocity to be high enough to give a suitable Reynolds number, the same equation has been used to compute the airside heat transfer. In this case, the only two thermal resistances that regulate the heat transfer are the airside and the waterside ones, because no material is between the bath and the air.

3.6.1.1.4 Evaporation

As shown in Figure 3.5, heat loss occurs because of convection, the effect of the car body heat capacity and evaporation. When a liquid is exposed to unsaturated air, which means that the air's relative humidity is lower than 100%, its vapor pressure is lower than saturation, and the liquid tends to evaporate. But for this process to happen the vaporizing liquid molecules have to absorb a determined amount of energy, called latent heat. The specific latent heat, i.e. the latent heat per unit mass, is a property of the liquid. Trying to estimate the evaporation rate is then very important to compute the heat loss because of this process.

Assuming that the air flow is large enough to renew the air above the dip tank at a rate that is orders of magnitude higher than the saturation rate due to evaporation, it is possible to consider the humidity of the air that is in contact with the top surface of the bath constant. In this way, it is possible to estimate the evaporation rate of the bath, using the equation [22]:

$$\Phi_{ev} = (25 + 19v)A(x_s - x)/3600 \tag{10}$$

in which Φ_{ev} is the mass of water (kg) that evaporates every second, v is the air speed on the free surface (m/s), A is the surface area of the fluid in contact with the air (m^2), x_s is the absolute humidity at saturation (kg/kg) and x is the absolute humidity of the air (kg/kg). This equation, with the two empirical parameters, 25 and 19, is suitable for liquids that behave like water [22]. Once the evaporation rate has been computed, multiplying it by the specific latent heat allows the calculation of the heat loss due to evaporation.

3.6.1.1.5 Car heat capacity

The car body enters the first dip tank at the plant ambient temperature. The driving force of heat transfer is a temperature gradient, and since the fluid contained in the tank is warmer than the ambient, the car bodies draw heat from the bath. This is the only heat loss that depends directly on the throughput: the higher the production rate, the bigger the heat loss.

However, this value is not easily estimated. The car body does not have enough time to heat up completely to the same temperature of the bath, therefore a complex study would be required to investigate the mechanisms of the heat transfer while the vehicle is submerged. Numerous parameters would play a role in this phenomenon, such as the velocity of the car body as it is moved in the bath, the shape of the vehicle, the amount of coating deposited up to the phase that is being analyzed, and so on. For the purpose of this work, under the given circumstances, the car body was assumed to heat up uniformly to the temperature of the bath, and a correction factor was multiplied by the value of the thermal power, accounting for all the effects of the considerations above. This parameter has been used to calibrate the model, in such a way that the energy consumption of the dip processes mirrored the results obtained from the computations of the left hand side of the model in Figure 3.3. Therefore, the equation used is simply:

$$\dot{Q}_{cb,dip} = F_{cb}(JPH/3600) \cdot m_{cb} \cdot c_{cb}\left(T_b - T_{plant}\right) \tag{11}$$

where $\dot{Q}_{cb,dip}$ is the heat loss due to the car body heat capacity (W), F_{cb} is the correction factor, c_{cb} is the specific heat capacity of steel (J/kg), m_{cb} is the mass of the car body (kg), JPH is the hourly production rate (car bodies/h), T_{plant} is the plant air temperature and T_b is the bath temperature (K).

3.6.1.2 Bring-up

Because of the continuous thermal losses, after a shutdown period in which the heat exchangers have not been operative, the bath temperature can drop significantly. Before the restart of production, the temperature of the fluid has to be brought to the set point level again. This means that every time that the plant shuts down for more than a shift, extra-consumption due to the start-up of the production process has to be considered.

Moreover, after a certain number of vehicles are dipped into the bath, the fluid has to be renovated (drained and refilled). Usually, it is water or water-based, and the tank is filled with city water at a lower-than-ambient temperature before chemicals are added. In the case of a renovated bath, the start-up consumption is significant, and has to be taken into account.

The temperature bring-up phase does not last for more than two hours. This allows the neglect of the thermal losses during this phase, that are negligible compared to the relatively huge amount of energy needed to heat up, on average, 300 cubic meters of water per tank. Considering the SHAP tanks, it is common that after a weekend shutdown the temperature of the bath drops by 5.5 °C, and to take it back to normal operative values, less than 40 minutes are needed. This model then, simply added to the consumption during normal operations the heat capacity of the bath, multiplied by a value around 5.5 °C if the shutdown lasted less than two days, or 10°C if the shutdown lasted for three to four days, and it assumed the bath to be at ambient temperature for longer shutdown periods. In case of a renewed bath, whose frequency can be programmed by the user, the energy was computed assuming the initial temperature of the bath to be at city water temperature. The general equation for the start-up consumption is:

$$Q_{su} = \rho_{bath} \mathrm{V}_{\mathrm{bath}} c_{bath} \Delta T \tag{12}$$

In which Q_{su} is the energy consumption for the start-up (J), $\rho_{bath}$is the bath fluid density (kg/m^3), V_{bath} is the volume of the dip tank (m^3), c_{bath} is the specific heat capacity of the bath fluid (J/kgK), and ΔT is the temperature difference between city water and the operating tank (K).

3.6.1.3 Other energy users: fans and pumps

The thermal energy needed by the dip baths, supplied by the heat exchangers, is obtained by letting hot water, which has been previously heated up using natural gas, flow into the hot side of the device. Natural gas is then the energy carrier that is responsible for the dip tanks bath temperature regulation, and the amount consumed was the ultimate result of the model computations. To get to this value it was necessary to divide the heat load supplied by the heat exchangers by the efficiencies of the heat exchangers, the distribution network – i.e. considering the heat losses through the pipes that take hot water from the furnace to the heat exchanger – and of the furnace itself. These efficiencies are generally high. Gas furnaces have gone through much development during recent years, and nowadays their efficiency is fairly high.

Although the main dip processes module accounts for natural gas consumption, in these processes a significant amount of energy is spent to run fans and pumps too, by means of electricity. One aim of this model was to differentiate the energy consumption by energy carrier; therefore the computations for this part have been carried separately.

Pumps' consumption data have simply been carried through from the equipment data – the left hand side of Figure 3.3. This choice is due to the difficulty in linking the pumps power consumption to the process variables, and to their intrinsic constant running characteristic, that does not depend on production rate or on some other external boundary conditions. Moreover, the number of pumps and the complexity of them wouldn't allow for a simple analysis: each phase of the phosphating and e-coat has different pumps, with different pressures and large ranges of flow rates. With a toggle in the model the user can select whether to shut the pumps – as well as fans – down during the plant shutdown time or to keep them running.

Fans consumption instead has been computed starting from the process requirements. Each operation requires a determined air flow rate, and multiplying the volume flow rate ($\dot{V}$, m^3/s) by the pressure drop (Δp, Pa) that has to be overcome by the fan – the average of which has been computed using the equipment data, specifically the pressure drop across the filters – and taking into account a fan efficiency factor – which is due to the non-ideal flow on the fan blades and is approximately 75% – the equation used was then:

$$P = \Delta p \dot{V} / \epsilon_{fan} \quad (13).$$

Every motor in the plant has been assigned a mechanical efficiency value of 95%, according to the datasheet of the installed equipment.

3.6.2 Ovens

In a paint shop, after each layer is deposited on the car body surface, the coated vehicle is cured in an oven. The phases that need this baking process are:

- e-coat
- sealant and foam application
- primer surfacer (powder)
- basecoat
- clearcoat.

Recent developments allowed eliminating a baking phase between the basecoat and clearcoat, substituting it with a quick "heated flash off" that dehydrates the basecoat to a value of 80% solids. As previously discussed, eliminating a separate basecoat oven is an effective way to cut energy expenses. Modern high output and flexible plants, however, have multiple, parallel lines, especially for e-coat curing and topcoat application, which result in more than one oven per phase. This model manages the schedule through the calendar module in such a way that the user can always control and decide which ovens to activate, if the production rate does not exceed the production capacity of the lines that are activated.

Oven technology can vary: "ordinary" convective ovens can be used, as well as radiant and infrared ones or any hybrid among these. Since this model has been created for the SHAP paint shop, the oven technology used in the model reflects the situation at the SHAP.

The operative principle of a convective oven is rather simple; an air flow at a certain temperature is blown at the body, according to the design specifications, and part of this flow is recirculated, while a – usually – small part of it is exhausted and substituted with fresh air. The scheme in Figure 3.8 shows how a single zone oven works. Ovens usually have multiple zones, and each zone has its own heater box, fresh air intake and exhaust.

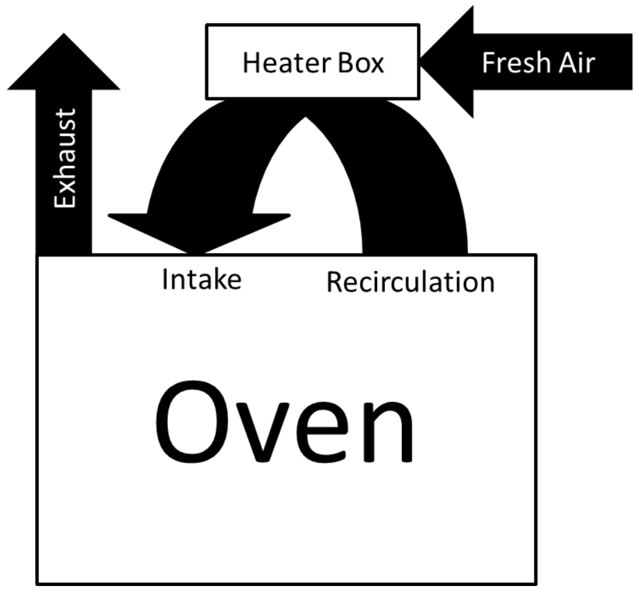

Figure 3.8 – Overall airflow in a coating oven

To estimate the thermal energy that has to be supplied to an oven for its normal operations it was important to identify the correct thermal balance, treating the oven as an open system with mass transfer through the steady-state intake-exhaust flow and energy transfer through the walls, that will be referred as "heat losses" in the following. All the assumptions of Section 3.5.1 are considered valid here.

Considering that some enthalpy is wasted through the exhaust – usually directed through a post treatment device for pollution control – and that the same heater box adds thermal energy to both the fresh air flow and the recirculated air flow, it is possible to compute the thermal balance for the open system. In Figure 3.9, the schematic diagram exemplifies this concept. Other heat losses include: convection, the effect of the car body heat capacity – analogous to the analysis for the dip processes, but this time the car body was assumed to be heated up to the oven temperature before exiting it – and the air infiltration enthalpy loss. This latter is actually due to the infiltration of cooler air through the strong downdrafts that seal the oven chamber. Since the infiltration air temperature is almost equal to the plant temperature, its net effect is of subtracting thermal energy from the system, and adding mass to the exhaust flow: more hot air is exhausted to equal the cold infiltration air. The result of the computation of this overall balance was considered the heat added to the recirculation air. The heat added to the intake air is an action that is outside the boundaries of the oven alone, and it has been taken into account in the thermal balance solution (Section 3.6.2.1.4).

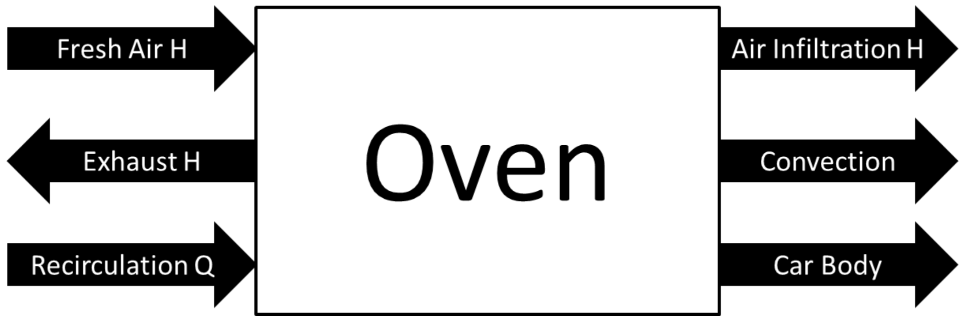

Figure 3.9 – Oven heat loss diagram

3.6.2.1 Steady-state conditions

3.6.2.1.1 Convection analysis

The convection heat transfer computation was similar to the one discussed in Section 3.6.1 for the dip processes. This time, convection through the bottom surface has been neglected as well, while the heat loss through the inlet and outlet apertures was due to air infiltration. Due to the high air motion inside the oven, the inside flow was considered to be turbulent, and Equation 9 has been used to compute the inside heat transfer coefficient for both the sides and the roof. The walls are again a sandwich of metal sheets and an insulation layer; therefore Equation 5 has been used for the computation of the conduction heat transfer coefficient. The external heat transfer occurs by natural convection, since the air motion depends exclusively on buoyancy forces. Therefore, the external coefficient for the sides has been computed using Equations 6, 7 and 8.

The external heat transfer coefficient for the roof has been computed considering the surface as a flat plate, with natural convection on top of it [21]. In this case, the equation for the nondimensionalized coefficient – Nusselt number – is simply:

$$Nu = 0.15 \cdot Ra_L^{1/3} \qquad (14).$$

3.6.2.1.2 Car body heat capacity

As previously discussed, one of the assumptions that has been made is that the car body gets heated up completely before exiting the oven. This is reasonable, due to the relatively long baking time, which is around 30 minutes. Moreover, since the carrier is completely inside the oven, the same consideration can be made about it. The car-carrier ensemble was assumed to enter the oven at the plant temperature, and the heat withdrawn from the oven chamber was computed as:

$$\dot{Q}_{cb,ov} = (JPH/3600) \cdot (m_{cb} c_{cb} + m_{carrier} c_{carrier}) \cdot (T_{ov} - T_{plant}) \qquad (15).$$

T_{ov} is the temperature inside the oven (K), and $m_{carrier} c_{carrier}$ is the heat capacity of the carrier section associated with each car (J/K).

3.6.2.1.3 Air infiltration

An oven has to be sequenced in the assembly line after the process for which it needs to cure the output, and because of the continuous flow of material in and out of it, physical doors are not commonly used. Some solutions help to keep the internal volume of the oven sealed, such as the positioning of the oven at a higher level, with an enclosed incline before the entrance and a decline at its exit. Moreover, a strong air downdraft creates an “air door” that keeps the hot air inside the oven chamber, and it is usually called an “air seal”. Although these solutions are effective, since the ovens’ environment is usually at negative pressure, some air manages to break through the air seal and “infiltrate” the oven.

To analytically estimate the infiltration flow is extremely complex, and not in the scope of this project. Moreover, design values for this phenomenon are available, and can be easily implemented in the model, considering a virtual steady-state flow that accounts for the higher exhaust volume, due to infiltration, and the low enthalpy inlet flow.

3.6.2.1.4 Thermal balance

The scheme in Figure 3.10 contains all the flows that are accounted in the thermal balance for the computation of the natural gas consumption of an oven. The solid, straight arrows represent mass transfers while the curved arrows represent heat transfers. The heat losses flux is the sum of the convective heat transfer and the effect of the heat capacity of the car bodies. The dashed line encloses the control volume, whose boundaries are used to compute the mass and the energy balances in Equation 16 and 17.

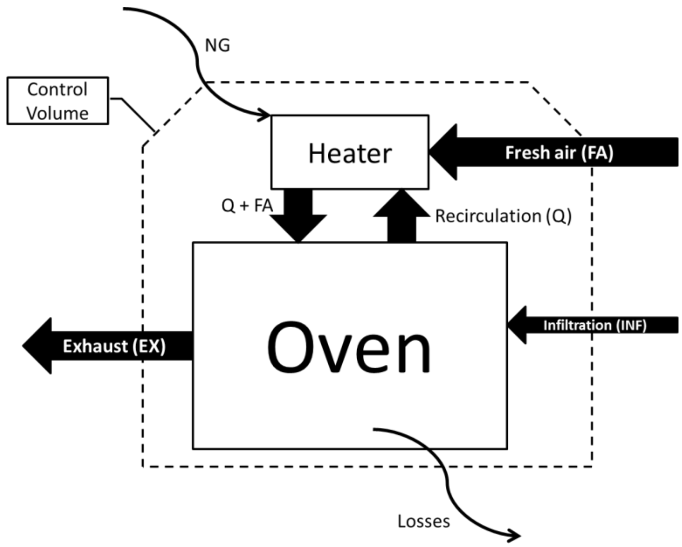

Figure 3.10 – Thermal balance scheme for an oven

First, the mass balance equation can be written:

$$\dot{m}_{FA} + \dot{m}_{INF} = \dot{m}_{EX} \tag{16}$$

in which $\dot{m}_{FA}$ and $\dot{m}_{INF}$ are the fresh air and infiltration air mass flow rates (kg/s), and $\dot{m}_{EX}$ is the exhaust mass flow rate (kg/s). Then, the balance of the energy flows can be computed:

$$\dot{m}_{FA} c_p T_{out} + \dot{m}_{INF} c_p T_p + \dot{Q}_{NG} = \dot{m}_{EX} c_p T_{ov} + \dot{Q}_{loss} \tag{17}$$

where c_p is the specific heat capacity of air (J/kg·K), T_{out} is the outside air temperature (K), T_p is the plant temperature (K), $\dot{Q}_{NG}$ is the heat added to the control volume by the natural gas (W), $\dot{Q}_{loss}$ is the heat lost by the control volume due to heat transfer through the oven's walls and to the car body (and carrier) heat capacity (W). Substituting Equation 16 in Equation 17, Equation 18 was obtained, to compute the required energy that comes from burning natural gas:

$$\dot{Q}_{NG} = \dot{Q}_{loss} + \dot{m}_{FA} c_p (T_{ov} - T_{out}) + \dot{m}_{INF} c_p (T_{ov} - T_p) \qquad (18).$$

T_{out} was taken from the previously discussed weather model, and it is affected by a variability due to the day/night cycle and to the seasonal fluctuation. Arranging the shifts and the production schedules can have an effect on the ovens' natural gas consumption.

3.6.2.2 Bring-up

For the ovens' start-up, all the considerations that have been made regarding the dip tanks, in Section 3.6.1.2, are valid. It is possible to divide the start-up period in two distinct phases, heating and stabilization. In the first one, the chamber inside the oven has to be brought to the operating temperature. Since this operation happens relatively quickly, heat losses were not considered. An air volume of twice the capacity of the oven chamber was considered to be heated up, to account for the capacity of the recirculation system. The air at the beginning was considered to be at the same temperature as the plant environment. The second phase, stabilization, is defined by the user, who can set the time period that has to be waited before the beginning of the production with the oven running at set point temperature. In this phase, heat losses were included. In the simulations that have been performed for this thesis, a stabilization time of 2 hours was used.

3.6.2.3 Electrical consumption

The ovens are among the biggest users of electricity in a paint shop. With no lights inside and no natural gas supply pumps, the electricity is used almost exclusively by the fan motors. This model considered the fans to be active whenever the oven was running, in any condition: bring-up or normal operation. The user can toggle the deactivation of the fans when an oven is not operative.

The air quantity that has to be moved by the fans inside the ovens can be obtained by the model in different ways, depending on the availability of the input data. It can be, in a decreasing preference:

- inserted directly by the user;
- retrieved from the equipment data, in the STEP 1 and STEP 2 sheets;

Every zone of the oven has a supply and an exhaust fan. To estimate the energy consumption of the ovens' fans, the pressure drop across the whole air loop – intake filters, kinetic energy increase, recirculation filters and kinetic energy increase – has been taken into account. The equation that was used to estimate the fan motors' consumption is Equation 13. The volume flow rate that was used for the computation was the actual volume flow rate, instead of the flow rate at standard conditions, which was used to compute the fresh air mass flow rate in Equation 18.

3.6.3 Booths and decks

In a paint shop there are some processes that require enclosed sections called booths. The purpose of the main booths is to guarantee that the environmental conditions reflect the strict needs of the spray processes, such as the primer surfacer, the basecoat and the clearcoat application. The air has to be treated and conditioned to guarantee the perfect quality of the outcome. As for the ovens, since the weather is variable during the year, the energy consumption of the booths is affected by daily and yearly fluctuations.

Working decks were treated as booths. The requirements can change, but their structure is analogous, and that makes the sub-model of the booths applicable. The application of foam and sealer gel is performed in the main deck of the paint shop. This operation is usually carried out by humans. Secondary booths and decks exist in many places in the paint shop, and they're used for rework, inspections and raw materials handling.

Booths and decks use energy in several ways. The primary energy users are the air treatment units, ATUs, that heat and condition the incoming air. The fan motors use another large share of the energy, while pumps use almost no energy, by comparison. Lighting impact is negligible, compared to the air conditioning and fan consumptions, and it may have less impact than the uncertainty of the other two. However, it was decided to include lighting in the booths and decks sub-model, because while it does not add any significant result relative to the overall energy consumption, its absolute value can help in understanding what is the impact of light management in an automotive paint shop, and its result can be completely decoupled from the other energy expenses; this model can be then used to verify the savings brought by the shutdown of the lights in the booths, or the amount of waste when they are not turned off.

3.6.3.1 Air treatment

As already mentioned, most booths and decks require that the supplied air condition be stable during production. This means that the air treatment units must work to satisfy the set point requirement regardless of the external conditions. Some months require mixing and heating, other months require cooling and dehumidification. Moreover, spray booths are usually wet booths, with water flowing under floor grates that are pervious to the air downdraft, washing the paint particles contained in it away from the air flow. A large part of the air is then recirculated, while some of it is exhausted, sometimes after going through a device for pollution control. The air that is extracted from the scrubber – i.e. the stream for which the water has washed paint or coating particles away from the airflow – has gained humidity, and cannot be recirculated as such. It has to be mixed with fresh air and re-treated in the air treatment units or air recirculation units (ARUs).

Given the complexity of this analysis and the availability of a module, supplied by FCA, that has been studied and perfected during the years by CRF (Centro Ricerche Fiat), a FCA research and development facility in Orbassano, Italy the computations for this part have been "outsourced". The FCA ATU module is a MS Excel® workbook with specific Visual Basic code used to solve psychrometric equations. The paint shop model has been created in such a way that it can communicate with the FCA ATU module, autonomously sending inputs and collecting the outputs. The inputs required are the volume of air that needs to be treated, the recirculation percentage, the set point temperature and humidity and the weather data – the weather module of this project has been set-up in such a way that it can work as input for an external block. The outputs of the FCA ATU module are the energy that has been supplied to the air during the heating days, the amount of cooling that has been provided to the air flow and the water used for humidification.

The outputs of the ATU model are not the direct estimation of the electricity and natural gas consumptions. Specifically, the energy that is used to heat the air is given by a natural gas heater box that has an efficiency that is less than 100%, while the energy that is withdrawn from the airflow to cool it down is not the electrical consumption of the air conditioner compressor. The natural gas energy consumption is given by:

$$\dot{Q}_{ATU,NG} = \dot{Q}_{heat}/\epsilon_{ATU,h} \quad (19)$$

where $\dot{Q}_{heat}$ is the output of the ATU module (W), and $\epsilon_{ATU,h}$ is the heating efficiency of the ATU. To compute the electrical consumption due to the cooling of the airflow, the concept of coefficient of performance has to be introduced. The refrigeration cycle describes the operation of a machine that, using external work, extracts heat from a cold source and sends it to a hot reservoir. Without the external work, the machine would violate the 2nd law of the thermodynamics. The efficiency of a machine is normally the ratio between the output quantity of the device and the "cost" of the operation. But a more useful way to measure its effectiveness is the simple ratio between the desired effect, the heat withdrawn from the cold source, and the external work. This value cannot be called efficiency, because it is usually consistently higher than 100%, and it is known as the coefficient of performance, COP.

In an air conditioner, the external work is supplied to the refrigerant by the compressor, and the cold source that is further cooled is the ambient air. In this way, if two values in the COP equation (Equation 20), such as air flow cooling energy and external work, are known, it is possible to easily compute the third one. Therefore, to estimate the electrical power consumption of the compressor, considering the coefficient of performance to be 3.5, the following relation was used:

$$P_{comp} = \dot{Q}_{cool}/COP \quad (20).$$

3.6.3.2 Fans

The fan power consumption was estimated using Equation 13. To estimate the air volume flow rate for each booth or deck, the model could use several sources.

- If the user inserts the desired volume flow rate manually for a booth or a deck, the model uses the user input as its primary source to compute the fan's consumption.
- If the user does not insert the flow rate information but inputs the booth or deck floor area and the air flow requirement per unit area, the model computes the total flow rate using a simple multiplication.

- If the user inserts the floor area and the type of the booth or deck, the model uses general values stored in its library or set by the user.
- If the user does not insert any information about the floor area and the flow rate, the model computes the flow rate from the STEP 1 and STEP 2 sheets.

Fan operation can be controlled by the user during downtime and plant shutdown. These controls interact with the booth management algorithm that is described in the following sections.

3.6.3.3 Lighting

The estimation of the lighting consumption is done using the information about the booths size. Through an interface, the user can select the type of the booth among 4 categories:

- inspection
- generic deck
- generic booth
- technical.

For each category, the design specifications for the booths and decks report a required luminous power per unit area, or illuminance, depending on the purpose of the room, reported in Table 3.2. The total luminous power can be computed multiplying by the floor area, and normalized values of luminous power per unit power consumption typical of fluorescence lamps for industrial use were utilized to calculate the electrical consumption. 50 lm/W has been chosen as a typical value [23], [24]. The default type set by the model was the generic booth or deck.

Table 3.2 Illuminance levels for different types of booths

Purpose	Illuminance [ft-cd]
Inspection	180
Generic decks and booths	120
Technical	50

Equation 21 shows the computation for the estimation of the lighting electrical consumption. E_v is the illuminance (ft-cd = lm/m^2), and K is the luminous efficacy of the fluorescent bulbs.

$$P_l = (E_v \cdot A)/K \tag{21}$$

3.6.3.4 Booths and decks management

The model handles booths and decks as separate modules, using the same calendar and weather module as the other processes, but with an internal management of the production schedules. Since there are 3 color booths in parallel, the user can set and decide whether to deactivate individual booths according to the production rate and which to deactivate. Moreover, the color ovens are in line with the color booths, and their operation is strictly linked to the booths operation. In Figure 3.11, a screenshot of the interface for the color booths, it is possible to see the green panel for the selection of the booths to deactivate in case of low production rate, and the red cell that shows that color booth #1 is currently not in use.

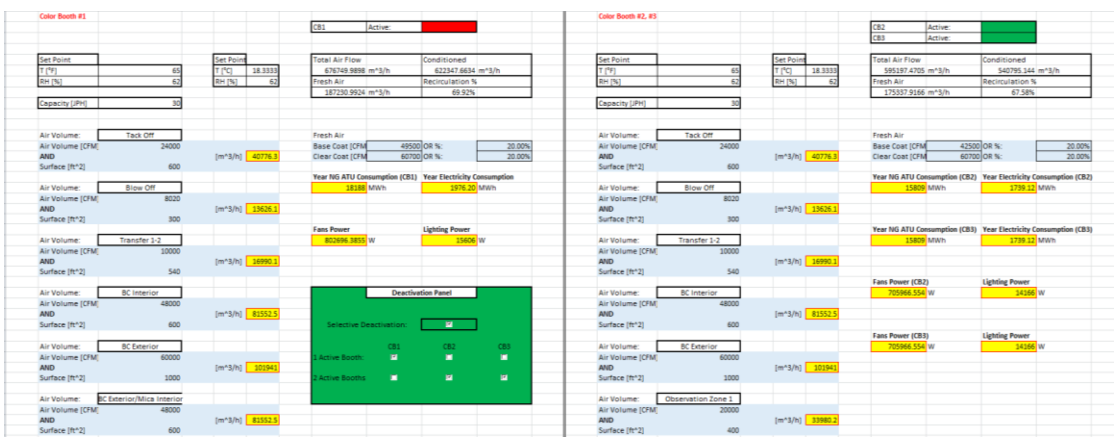

Figure 3.11 – Color booths interface

The user can act on another interface, called Variables, in which it is possible to set values for the required air flow per unit area or air speed, tell the model whether a booth, a deck or a zone is to be conditioned or not through a checkbox, select the purpose of the booth, deck or zone with a drop-down selector, and visualize the corresponding surface area. Figure 3.12 is a screenshot of the Variables sheet for color booth #1. Everything is color coded for quick reading.

Color Booth #1							
Air Speeds			Conditioned?		Lighting		Area [ft^2]
Tack Off	[fpm]	40	☐		Technical	Technical	600
Blow Off	[fpm]	27	☐		Technical	Technical	300
Transfer 1-2	[fpm]	18.5	☑		Technical	Technical	540
BC Interior	[fpm]	80	☑		Booth	Booth	600
BC Exterior	[fpm]	60	☑		Booth	Booth	1000
BC Exterior/Mica Interior	[fpm]	80	☑		Booth	Booth	600
Observation Zone 1	[fpm]	50	☑		Inspection	Inspection	400
Air Seal 1	[fpm]	33	☑		Booth	Booth	120
Air Seal 2	[fpm]	57	☑		Booth	Booth	350
Transfer/Flash 3	[fpm]	7.5	☑		Technical	Technical	270
CC Interior	[fpm]	80	☑		Booth	Booth	600
Transfer/Flash 4	[fpm]	7.5	☑		Booth	Booth	270
CC Exterior	[fpm]	60	☑		Booth	Booth	1000
Observation Zone 2	[fpm]	100	☑		Inspection	Inspection	400
Air Seal 3	[fpm]	35	☑		Technical	Technical	120

Fans		
Average Δp across filters	["WC]	6
Average O/A Efficiency	[-]	70%

Lighting			Type
Lighting Intensity Booths	[ft-cd]	120	Booth
Lighting Intensity Inspection	[ft-cd]	180	Inspection
Lighting Intensity Technical	[ft-cd]	50	Technical
Specific Intensity Light Bulbs	[lm/W]	50	

Figure 3.12 – Color booths variables set-up

3.7 Scenarios

The model has been generated to be able to run simulations of several scenarios, varying production rate, asset utilization, shift organization, and shutdown scheduling. The aim of this project was to run some test scenarios in order to understand the behavior of the paint shop as a response to the change of pre-determined parameters. The following variables have been controlled and changed according to the scenario purposes:

- production rate;
- operation of:
    - fans;
    - ATUs;
    - dip process heat exchangers;
    - lights;
    - agitator pumps;
- shift organization;
- shift length;
- vacation scheduling.

3.7.1 Scenario 1

The first scenario was a typical year of mass production. The manufacturing target was 180,000 vehicles, produced in one 10-hour shift per weekday, starting at 6 in the morning. The plant was shut down on the weekend. Two vacations with complete shutdowns were included, for a total of three weeks. The plant throughput was close to its maximum capacity, at 74 jobs per hour, and all the parallel production lines were activated. This scenario has been used for high-level model calibration, and should mirror the current conditions of the plant. Some data are summarized in Table 3.3, and the calendar schedule is shown in Figure 3.13.

Table 3.3 – Main parameters for Scenario 1

Parameter	Value
JPH	74
Total production	181,300
Shifts per day	1, 10h
Shutdown days	120

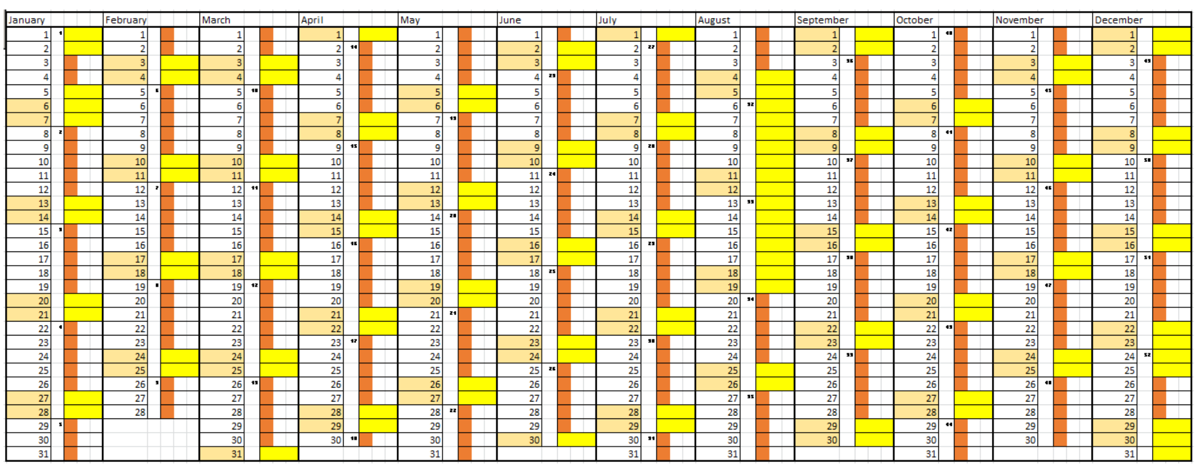

Figure 3.13 – Scenario 1 calendar

3.7.2 Scenario 2

Scenario 2 represents a completely different strategy to fulfil the same production requirement in a year. The production rate has been set to 53 jobs per hour, and the selective deactivation of the color booths has been utilized, using only color booths 2 and 3. A production day is organized in two shifts, 7 hours long, and during the weekends the systems are shut down. In Table 3.4 and Figure 3.14 some information is summarized.

Table 3.4 – Main parameters for Scenario 2

Parameter	Value
JPH	53
Total production	181,790
Shifts per day	2, 7h
Shutdown days	120

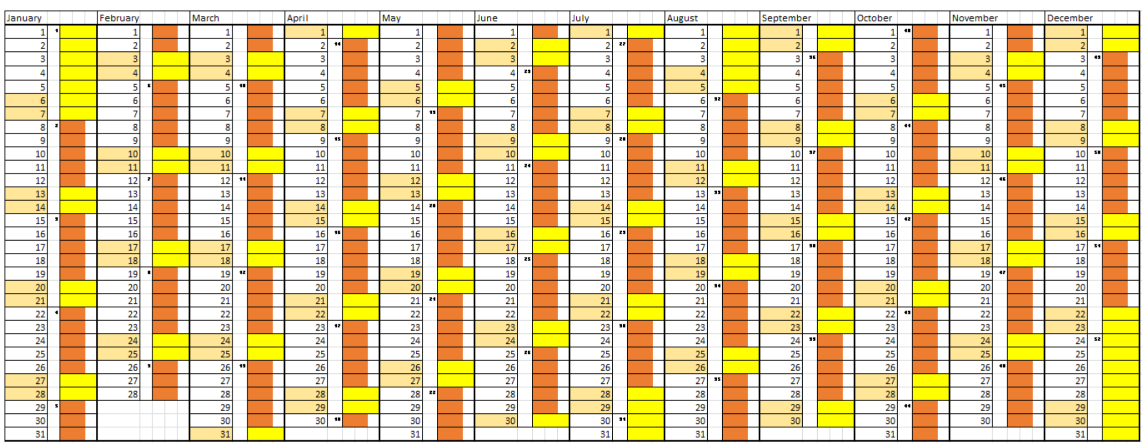

Figure 3.14 – Scenario 2 calendar

3.7.3 Scenario 3

Scenario 3 had the same structure as scenario 1 but with no weekend shutdown, and its calendar schedule is shown in Figure 3.15. It has been included in this study, along with Scenario 4, to evaluate the impact of systems shutdown during the weekend and of the Monday morning startup operations. Three weeks of summer and winter closure have been kept, and total production is the same as scenario 1, as reported in Table 3.5.

Table 3.5 – Main parameters for Scenario 3

Parameter	Value
JPH	74
Total production	181,300
Shifts per day	1, 10h
Shutdown days	26

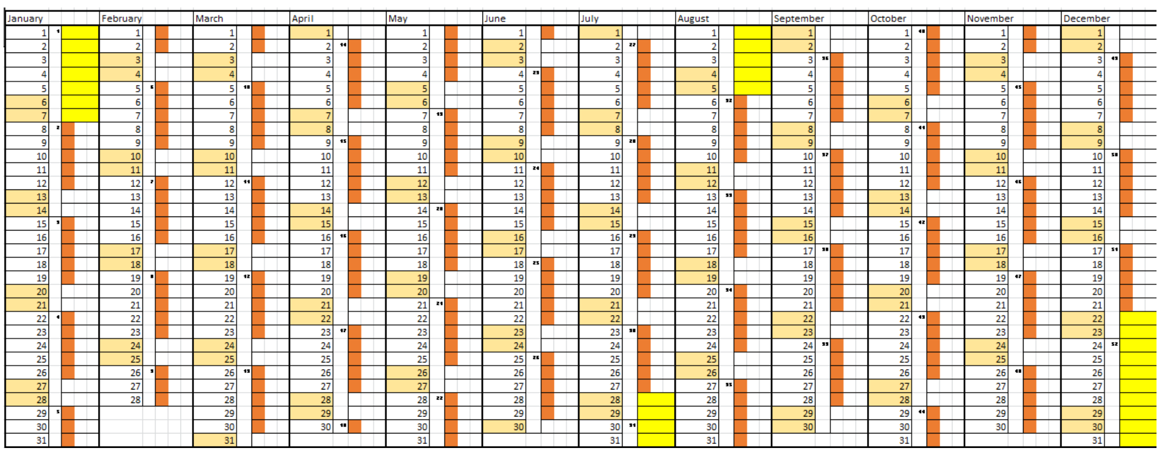

Figure 3.15 – Scenario 3 calendar

3.7.4 Scenario 4

Scenario 4 was a modification of scenario 2, without systems shutdown during the weekend. The vacation closures have been kept the same, as well as the total production and the shift organization. This scenario is used to evaluate the effect of the weekend shutdown in the case of different shift organization and asset utilization. In Table 3.6 the data relative to this scenario have been summarized, and Figure 3.16 shows the screenshot of the calendar.

Table 3.6 – Main parameters for Scenario 4

Parameter	Value
JPH	53
Total production	181,790
Shifts per day	2, 7h
Shutdown days	26

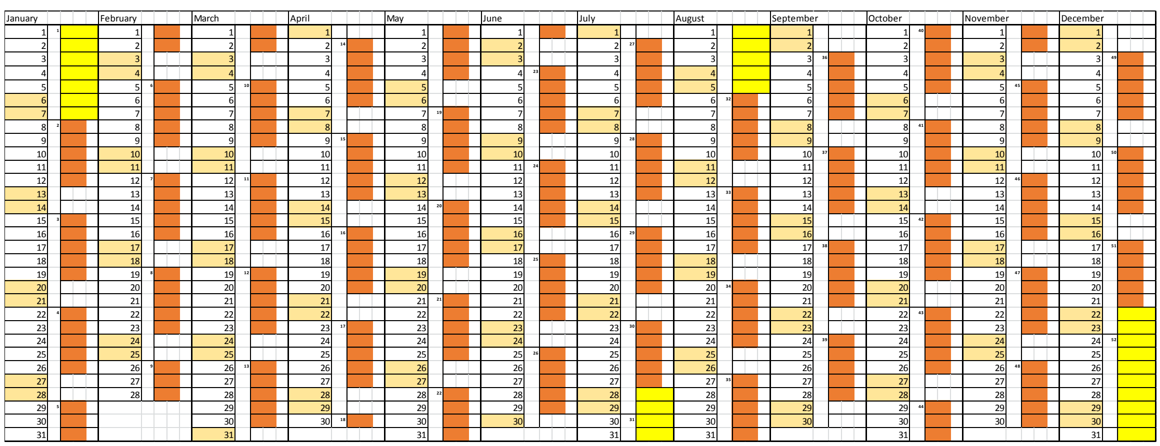

Figure 3.16 – Scenario 4 calendar

3.7.5 Scenario 5

Scenario 5 has been introduced determine how to minimize the losses that limit normal production efficiency. Although it is practically impossible to be applied as a production plan, the model has been tested to understand how far the efficiency margin can be pushed. The purpose of this scenario is to avoid having time in which the systems are operative but no vehicle is coated. Moreover, the production is organized to minimize the quantity of startup operations, requiring 1 major startup at the beginning of production, on December 16, as in Figure 3.17. The plant would be operative for 15 weeks and 5 days, as summarized in Table 3.7.

This scenario, as already stated, is impossible to be actuated, because it considers the production rate to be equal to the maximum capacity. Moreover, this production strategy would create enormous inventory value at the end of the production period, potentially resulting in a considerable loss for the company.

Table 3.7 – Main parameters for Scenario 5

Parameter	Value
JPH	75
Total production	180,000
Shifts per day	3, 8h
Shutdown days	265

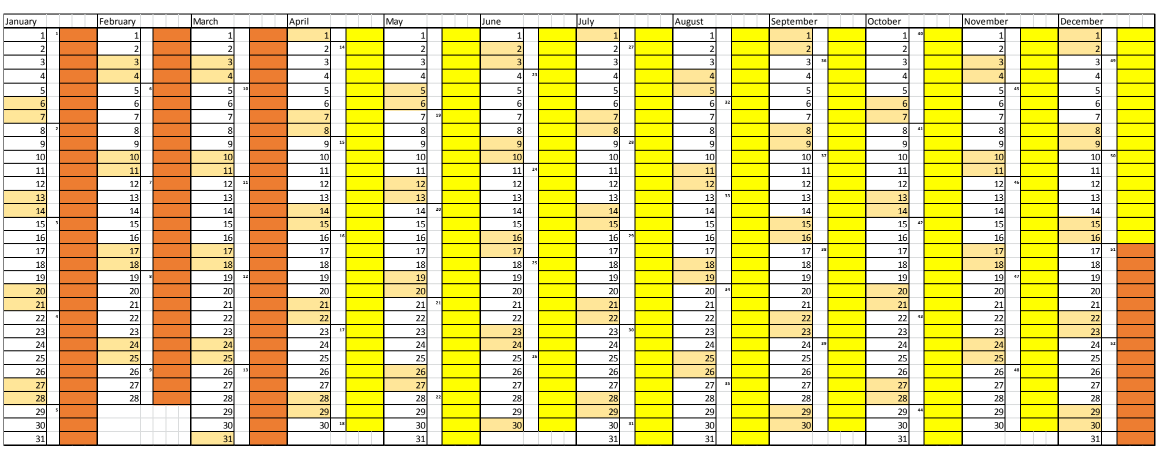

Figure 3.17 – Scenario 5 calendar

4 Calibration and Results

4.1 Calibration

The third phase of the model generation was the calibration. At this point, the major uncertainty sources had been identified, and adjustable parameters in the analytic model (right hand side) had been configured to be able to slightly modify their values to make the result of the model closer to reality (left hand side). The following rules have been set.

- The calibration has been performed using instantaneous power as a reference where possible. Trying to compare and tune the energy consumption per unit of production can induce some errors, because its value depends on the shift distribution, running time, and other process variables. Averaging in time has therefore been avoided.
- The calibration was carried out preferably by isolating its effect on real equipment. This allowed one to calibrate the model at a lower level, on a detailed base, so the outcome of the model is more reliable. STEP 1 worksheets were used to perform this operation with as much detail as possible.
- When it was not possible to isolate the effect of the calibration, or when several phenomena interacted for the energy load of a single element – such as for the heat exchangers of the dip tanks, whose thermal load is due to several types of heat loss – two scenarios that were likely to occur were:
  - each phenomenon that contributes to the element energy consumption had a constant characteristic, and was not linked to a parameter that was part of a case study analysis.
  - one of the phenomena that made up the element energy consumption depended on the production rate or was linked to a parameter that could be modified by the user – i.e. the heat transfer through walls is strictly related to the thickness of the insulation, which could be modified by the user with the purpose of evaluating its effect on the heat exchanger load.

  If the calibration was performed on a set of constant and not modifiable parameters, a simple correction factor can be implemented, without affecting the quality and reliability of the model outcome. In the case of some factors that depended on production or on values that can be managed by the user, the other two scenarios that could occur were:

  - If it was possible to acquire secondary information and data from other sources, that can raise the level of knowledge of the result, and that can be used to investigate the energy consumption mechanisms of a determined sub-process, then the calibration procedure can be done according to this new information, without affecting the reliability of the model by a considerable extent. Taking the dip tanks as an example, the information that after a 48 hours shutdown the bath temperature dropped by 5.5 °C and that the bring-up lasts for 40 minutes has been used to estimate the total heat loss due exclusively to heat transfer through walls and to verify the heat exchangers' ratings.
  - If it was not possible to acquire secondary information that would help in the calibration process, and the difference between the real equipment consumption and the model was lower than 50%, it has been decided to leave the model as it is, considering the low impact of this offset on the whole paint shop energy consumption result. If the difference was higher than 100%, then a correction factor was employed, but the result of the sub-process that had been calibrated lost some reliability for scenarios with heavy modifications of the actual conditions. For values higher than 50% and lower than 100%, common sense and hybrid solutions had to be used.

- When the offset between a model sub-process energy carrier consumption and STEP 3 worksheet computations was found to be less than 30%, no calibration was performed. This threshold has been decided due to the low impact of a single energy carrier consumption in a sub-process (phosphating, e-coat, powder booths, color booths, sealer decks, ovens and generic booths) on the consumption of the whole paint shop.

The model has been calibrated at a low level, within the sub-processes, comparing the results of each phase to the value obtained in the worksheet STEP3. The overall energy consumption has then been compared to the values in the literature, considering the differences between the SHAP paint shop layout and the average. Moreover, the plant utility bills have been used to understand how the model predicted the annual cost of the SHAP paint shop. Before applying the corrections, the targets for the calibration procedure have been identified, as reported in Table 4.1.

Table 4.1 – Calibration parameters for sub-processes

Sub-process	Energy carrier	Calibration parameters
Phosphating	Electricity	Fan efficiencies
	Natural gas	Correction factor for car body heat capacity
		Air speed for evaporation rate
E-coat	Electricity	Fan efficiencies
	Cold water	Correction factor for car body heat capacity
Ovens	Electricity	Fan efficiencies
		Ventilation system pressure drop
	Natural gas	Convection coefficients
Powder booth	Electricity	Fan efficiencies
		FCA ATU module
	Natural gas	FCA ATU module
Color booths	Electricity	Fan efficiencies
		FCA ATU module
	Natural gas	FCA ATU module
Decks	Electricity	Fan efficiencies
		FCA ATU module
	Natural gas	FCA ATU module
Generic booths	Electricity	Fan efficiencies
		FCA ATU module
	Natural gas	FCA ATU module

4.1.1 Phosphating

4.1.1.1 Electrical consumption

The phosphating process fan efficiencies have been set by averaging the ratio between the pumping work given to the air flow in the unit time and the power consumption of the fans in the STEP 1 and 2 worksheets, obtaining values between 60% and 75%. After comparing the power consumption obtained with the model to the computations using the equipment data there was no need for a calibration procedure. Pump energy consumption has been directly carried out in the STEP 3 worksheet, therefore it is assumed to mirror the real world value.

4.1.1.2 Natural gas consumption

The natural gas consumption is directly proportional to the heat loss of the dip tanks. The correction factor for the car body heat capacity was initially set to a value of 0.2, and the air velocity, contained in Equation 10, is known to be close to 1 m/s.

Assuming the heat exchangers' thermal loss to the environment to be the 5%, the values of energy consumption of the model were compared to the equipment data. Moreover, the convective heat transfer was verified using the information of the temperature drop after a weekend shutdown. After the comparison, the correction factor for the car body heat capacity was lowered to 0.17. In Table 4.2 and Table 4.3 the parameters for the calibration have been reported. Although the convective heat loss does not match the actual value perfectly, no corrections have been applied, because of the low impact on the overall pretreatment result.

Table 4.2 - Phosphating cleaning dip calibration

	Analytical Model	**Actual**
Convective heat loss	35 kW	39.7 kW
Winter consumption, F=0.2	329 kW	294 kW
Winter consumption, F=0.17	297 kW	294 kW

Table 4.3 - Phosphating dip calibration

	Analytical Model	Actual
Convective heat loss	35 kW	39.7 kW
Winter consumption, F=0.2	331 kW	299 kW
Winter consumption, F=0.17	298 kW	299 kW

4.1.2 E-coat

4.1.2.1 Electrical consumption

The assumptions for the phosphating electrical consumption were valid and used for e-coat, and no corrective actions have been required.

4.1.2.2 Cold water consumption

The same procedure as the phosphating process has been followed. The energy that is added through the recirculation pumps to the bath was larger than the heat loss. The first check was to verify the net heat transfer to be positive, based on the heat exchanger data. Then, the corrective factor for the car body heat capacity was carried through from the phosphating phase. In this case however, no information was available to validate the cold water consumption; therefore the result of the model could not be verified. The evaluation of the cooling water consumption is not one of the main targets of this project, and the problem was not further investigated.

4.1.3 Ovens

4.1.3.1 Electrical consumption

The fans' energy consumption was computed using the average efficiency from the equipment data. Therefore, no corrective factors have been used, as the model mirrors the actual values.

4.1.3.2 Natural gas consumption

The natural gas consumption, as previously discussed, can be split into a term that is relative to the fresh air intake heating, and another term relative to the recirculation re-heat. The first value uncertainty was relatively low, as the only parameter that can affect its result – apart from the airflow characteristics – is the heater box efficiency, which was high enough (95 – 98%) to confidently assume the result to be reliable. The thermal energy added to the recirculation flow, instead, depends on the heat losses through the walls, and convection parameters can be adjusted.

Baseline data about recirculation flow rate, inlet and outlet temperature of the return airflow are available and were used to compute the actual power that is required to re-heat the recirculation airflow. Moreover, natural gas readings for each burner are accessible through the FIS system, and have been used to verify the total consumption of each oven.

In the following tables, the data relative to the ovens' calibration are reported. It is possible to conclude that the estimation of the power required to heat the fresh air is reliable. Therefore, no corrective factor has been applied to the fresh air computation. However, the consumption linked to the recirculation air flow re-heating on average, is overestimated. As already discussed, the ovens were assumed to draw air directly from the outside, which reflects an overestimation of the ovens consumption. But the energy required to heat the intake air from the outside temperature to the oven set point temperature averages around 0.15 MW per oven, a value that is too low to justify the large error. Looking closely to the data in the tables, however, it can be noted that for the baking processes that are served by more lines in parallel, the error is smaller, while for the sealer oven, that alone cures the whole production of the paint shop, the error was close to 100%, suggesting that the shift is related to the ovens' throughput. It is possible to state, with a certain level of confidence, that the cause of the offset was in the estimation of the thermal energy withdrawn by the car body and the carrier that raise their temperature along the curing process. Going deeper, trying to access the root cause, it is possible to notice that no information relative to the mass of the carrier has been found, and the model has been generated with an algorithm that, in case of a missing piece of information, the required data is gathered from the previous sub-process module. The e-coat carrier mass has then been used by the model, and its value is greater than 750 kg. Since the correct value was still unknown at the time in which this dissertation has been written, a correction factor, F, of 0.6 has simply been introduced and is multiplied only to the heat capacity term. Its results can be seen in the following tables.

Table 4.4 – Effect of calibration on e-coat ovens

	Model	Model F = 0.6	Actual
Recirculation	1.64 MW	1.30 MW	1.38 MW
Fresh air (average)	1.05 MW	1.05 MW	0.91 MW
Total (average)	2.69 MW	2.35 MW	2.29 MW

Table 4.5 – Effect of calibration on sealer oven

	Model	Model F = 0.6	Actual
Recirculation	2.21 MW	1.74 MW	1.28 MW
Fresh air (average)	0.32 MW	0.32 MW	0.33 MW
Total (average)	2.53 MW	2.06 MW	1.61 MW

Table 4.6 – Effect of calibration on powder ovens

	Model	Model F = 0.6	Actual
Recirculation	1.58 MW	1.30 MW	1.68 MW
Fresh air (average)	1.57 MW	1.57 MW	1.46 MW
Total (average)	3.15 MW	2.87 MW	3.14 MW

Table 4.7 – Effect of calibration on color ovens

	Model	Model F = 0.6	Actual
Recirculation	2.14 MW	0.76 MW	0.74 MW
Fresh air (average)	1.13 MW	1.13 MW	1.01 MW
Total (average)	2.27 MW	1.89 MW	1.75 MW

4.1.4 Booths and decks

4.1.4.1 Electrical consumption

In booths and decks, electricity is used to power fan motors, lights and the air treatment units. The fan efficiency has been set, for each booth and each deck, averaging the efficiency of every fan obtained in the STEP 1 and 2 sheets, obtaining values between 60% and 75%, and the result mirrors the one computed using the equipment data. Light power consumption has not been calibrated, since there is no access to data for comparison, and, as already discussed, its value is extremely low compared to the other users, so it has not been considered an issue for the final result of the model. The air treatment units result was obtained using an external FCA module, and no data are available for comparison within the sub-processes. A verification procedure has then been carried out looking at the plant electricity bills and at some values contained in the literature. Although the literature does not provide precise information about it, in normal operating conditions, indicatively the electricity used in the paint booths accounts for 40% – 50% of the total, including ventilation [7], [4], [12], [5]. Using the first scenario, described in the following sections, the model estimated an electricity consumption of the whole paint shop of 42 GWh for a year of 365 days, of which 27 GWh was used by the color booths, the powder booth and the generic booths and decks, accounting for 65% of the total. If just the powder and color booths are considered (in order to match the “paint booths” as stated in the reference), their electricity share drops to 49%. These values can be considered acceptable, considering that the SHAP has a high output paint shop, with 3 color booths in parallel.

4.2 Results

Scenarios 1 to 5 have been run for the energy consumption estimation of a year of production. In the following, the results of these simulations are reported and discussed, comparing diverse scenarios and relating differences to strategy changes. Scenarios 1 to 4 have been compared among them, since they can be realistically adopted by the SHAP paint shop, while scenario 5 has been analyzed separately, because of its unique nature.

To make the analysis more consistent with industrial needs, a price per unit for the electric energy and natural gas has been set, and total expenses have been calculated. Without these parameters, it is impossible to put together the consumption of natural gas and electricity, because of the lower cost of the first one, and hence it would not be possible to evaluate the scenarios' benefit. The chosen values are reported in Table 4.8.

Table 4.8 – Specific energy cost

Energy carrier	Cost per kWh [$/kWh]
Electricity	0.0614
Natural gas	0.0128

4.2.1 Scenario 1

The first scenario consumption data are reported in Table 4.9. The chart in Figure 4.1 shows the trend of the electricity consumption throughout a year, while the one in Figure 4.2 reports natural gas use.

Table 4.9 - Scenario 1 results overview

	Energy	Cost
Electricity, total	42,702 MWh	$ 2,621,915
Natural gas, total	222,113 MWh	$ 2,841,259
Electricity, per car	235.53 kWh	$ 14.46
Natural gas, per car	1,225.11 kWh	$ 15.67

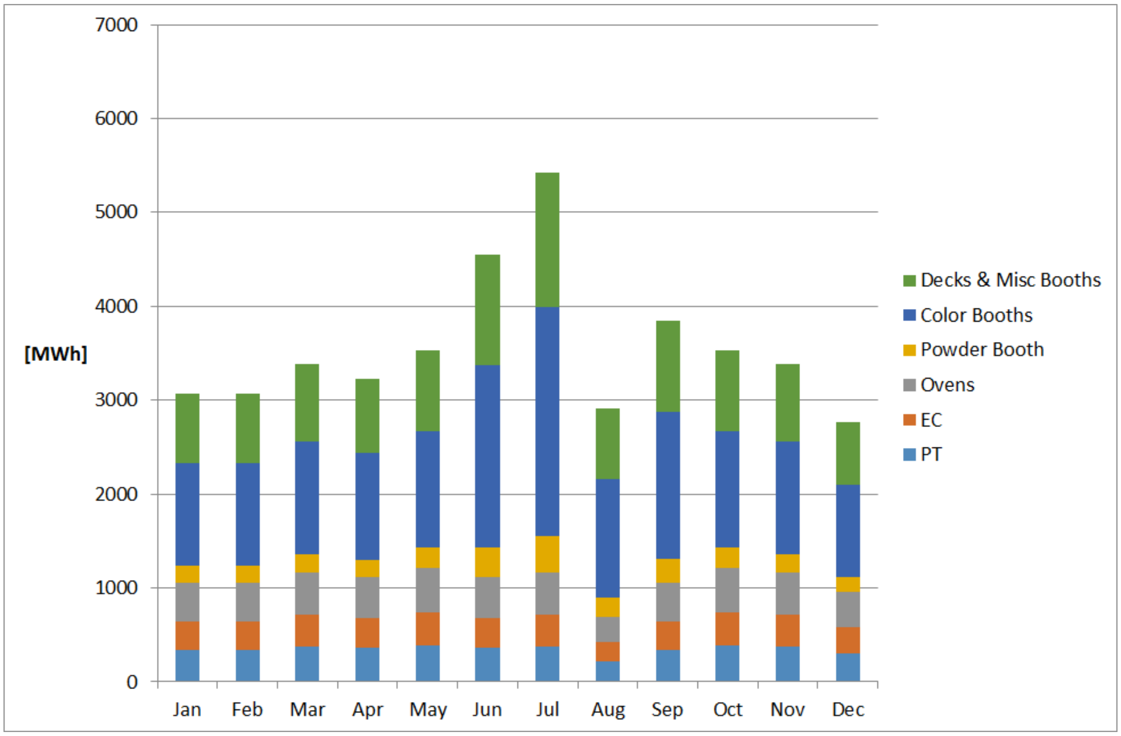

Figure 4.1 – Monthly electric consumption for Scenario 1

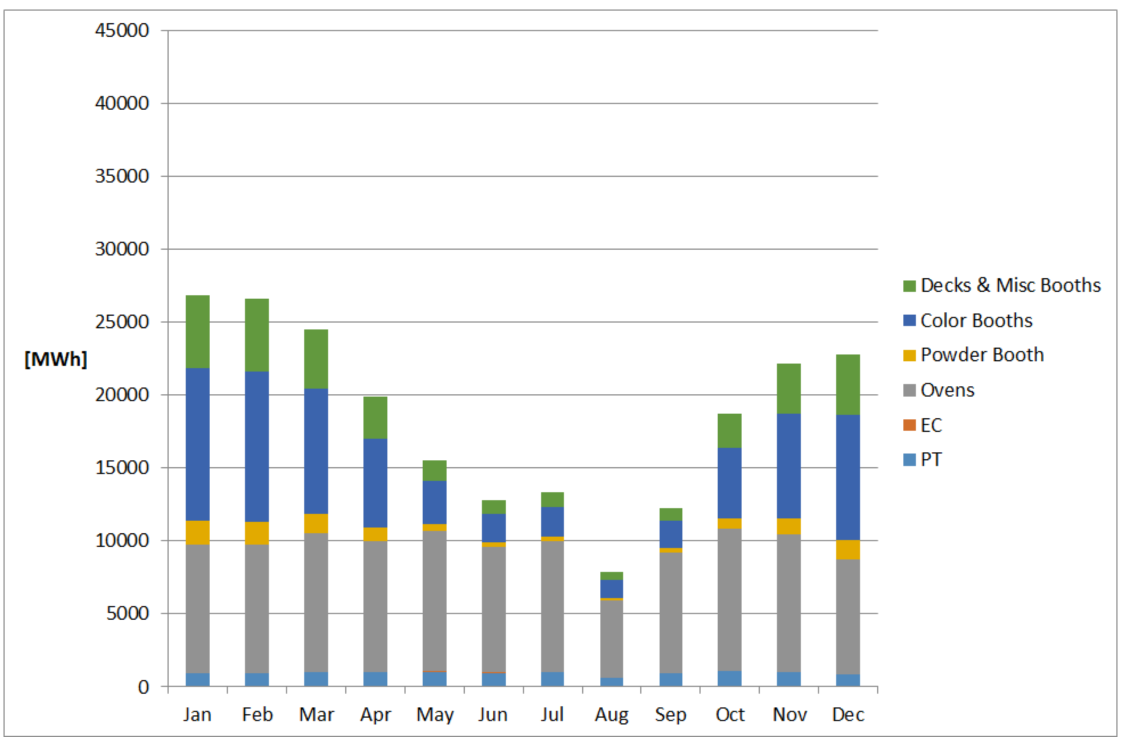

Figure 4.2 – Monthly natural gas consumption for Scenario 1

The expenditures for natural gas and electricity were very close to each other. Natural gas cost per car was slightly higher than electricity, mainly because of the assumption that the intake airflow of booths, decks and ovens is directly drawn from the outside, and not cascaded through the plant HVAC. The total energy cost per vehicle averages around $30, and the values of energy consumption per car match the literature values. In Figure 4.1 it is possible to notice that the electrical consumption has a variability that is directly proportional to the average outside temperature. Looking closer at the diagram, the yellow, blue and green bars – corresponding to all the booths and decks – appear to be the primary causes of this oscillation, while phosphating, e-coat and ovens show a constant trend. This is explained by the electricity users in each sub-process: in the pretreatment and the ovens, electricity powers fans and pumps, that are not susceptible to the external conditions, while a big part of electrical energy is used in the booths for the air conditioning, during hot summer days. Since the booths set point is higher than the outside temperature except for the months of July to September, the electrical consumption increases just for these 4 months. August and December are affected by vacation downtime, and their total value is lower than the average. The color booths appear to be the most important electricity users in the whole paint shop.

The timing for the natural gas consumption, as depicted in Figure 4.2, is opposite to that for electricity. Natural gas is used to heat the airflows coming from the outside, and to keep the dip tanks' temperature constant in time. Heat loss from the dip tanks depends on the production rate and on the plant temperature – heat transfer from the bath to the plant is driven by a constant temperature gradient. These two factors are constant throughout the year, and, as expected, pretreatment natural gas consumption does not change. Being careful to not consider the consumption in the months of August and December, the ovens also do not show significant changes, even though part of the natural gas is used to heat the airflow from the outside to the oven set point temperatures. This can be explained by the composition of two factors:

- oven set point temperatures (150 to 175 °C) are consistently higher than the average outside temperature, and the average temperature "jump" that the fresh air goes through (40 °C) makes the winter to summer difference less significant;

- only fresh air heating depends on the outside temperature, and fresh air intake accounts for a small part of the total airflow – depending on the oven, it can be lower than 7% – and is about the half of the ovens total consumption.

Therefore, as it can be seen in Figure 4.2, there is variability in the booths' and decks' gas consumption, as with electricity. Since the booths set point is higher than the outside temperature in the majority of the year, a large amount of natural gas is used to heat the fresh air intake. The booths set point temperature however, different from the ovens case, falls within the annual range of outside temperatures. The result is that during hot summer hours, the intake airflow has to be cooled down, by expending electric energy, and not heated up, lowering significantly the natural gas consumption. Some energy is still used to reheat the air after being dehumidified, in the ATUs. In the winter months, the color booths are the main natural gas users, while in the summer they drop significantly. As reported in Figure 4.3, even though the values are averaged throughout the year, the color booths alone are responsible for 35% of the total energy cost, while the ovens to only 30%.

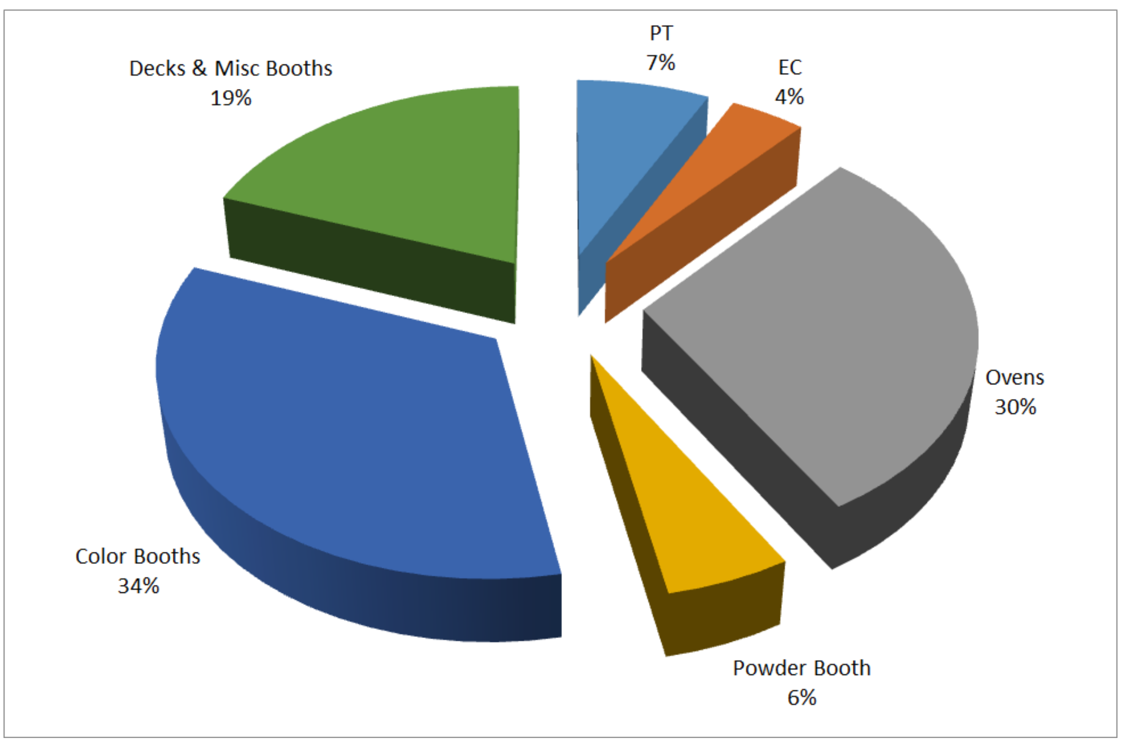

Figure 4.3 – Energy cost proportion per sub-process for Scenario 1

Figure 4.4 and Figure 4.5 report the same diagrams as Figure 4.1 and Figure 4.2, but they have been scaled to show the relative proportions for each month. It is possible to notice that, regarding electrical consumption and especially in the winter months, the contribution of color booths, ovens, and phosphating together with e-coat is almost comparable. Acting on each of these areas, then, would have the same impact on energy cost per produced vehicle. In the summer, the contribution of the color booths increases consistently, and they become 45% of the total electrical consumption.

Natural gas works similarly, with an almost equal distribution in the winter days. In the summer, however, because of the combined effect of the booths that do not need heating anymore, and of the ovens whose need for thermal energy does not change considerably, the ovens become the main natural gas users, averaging 65% in the months of June, July, August and September.

The chart in Figure 4.6 shows the trend of the unit cost during the year. It is interesting that it changes by 31% of its value between the minimum and the maximum. The reasons for this large fluctuation can be summarized as:

- a large fluctuation in the outside temperature, ranging from -20 °C (and lower) in the winter to 30 °C (and higher) in the summer;
- an incomplete view of the energy involvement in the painting process: as already stated, some elements such as building HVAC, building lights, compressed air, and conveyors have not been considered;
- the assumption of drawing air from the outside for booths, decks and ovens.

We can see that the function that describes the unit cost has not just one fluctuation throughout a year, but interestingly it rises again in the mid-summer months, leaving two valleys representing the lowest unit cost in the months of May and September. Ideally, the production should be brought towards these months.

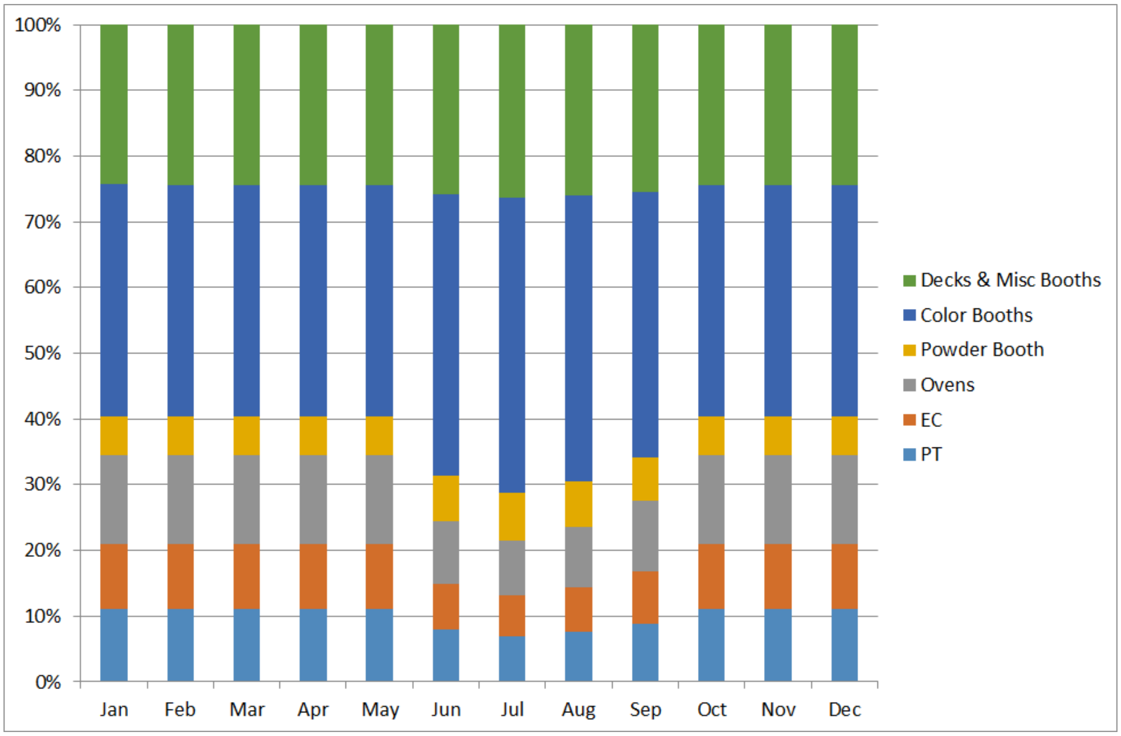

Figure 4.4 – Monthly electric energy share within paint shop for Scenario 1

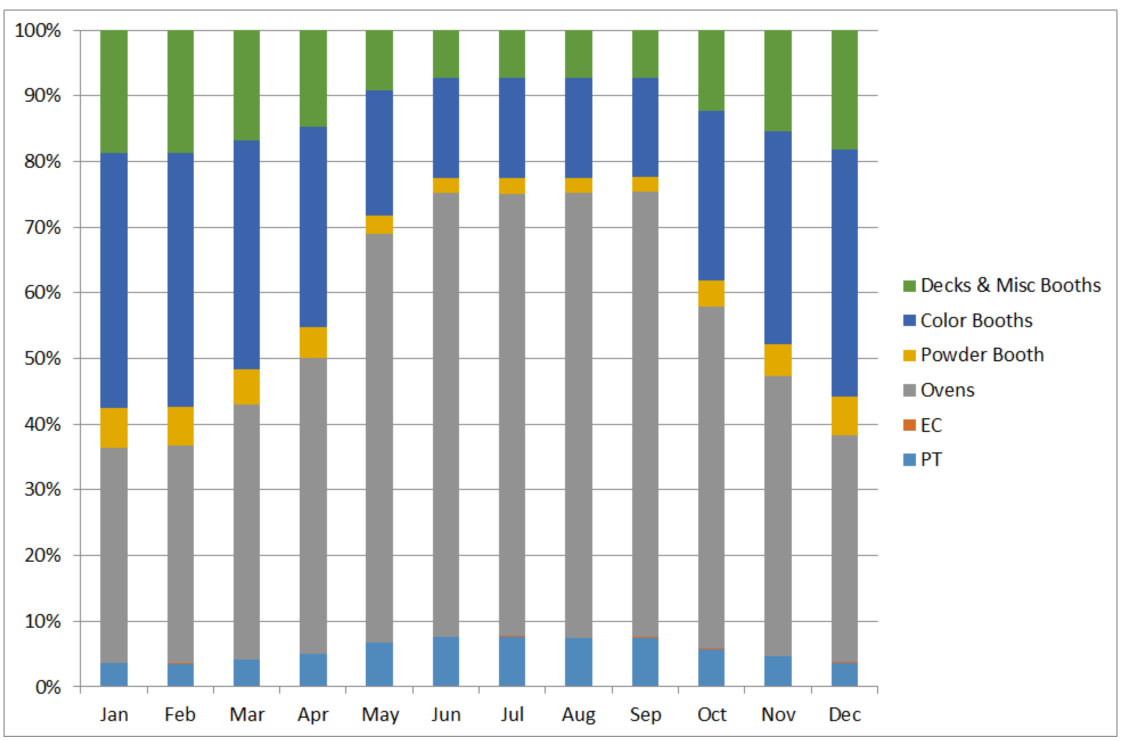

Figure 4.5 – Monthly natural gas energy share within paint shop for Scenario 1

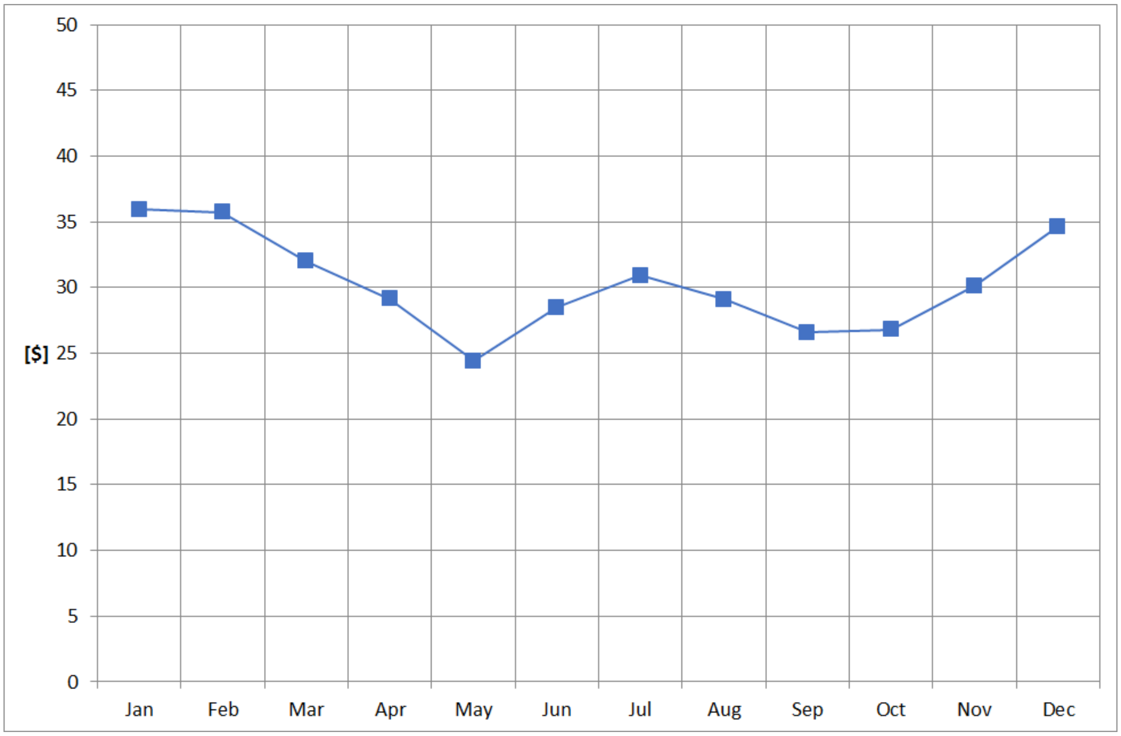

Figure 4.6 – Unit cost throughout a year for Scenario 1

4.2.2 Scenario 2

In Scenario 2, the production target was fulfilled in 2 shifts per day, each of them 7 hours long. The production rate was slowed down to 53 jobs per hour, and color booth #1, as well as its oven, was not used. The plant was shut down on the weekend, and on Mondays, production started with a rapid start-up. In Table 4.10 an overview of the energy consumption is reported. Although the production strategy is different from Scenario 1, the average cost per unit computed by the model is almost the same. The low production rate does not affect the energy consumption to a great extent, because of the deactivation of the parallel lines, while some energy is recovered by better utilization of the daily 24 hours, leaving just the night shift without production. The difference between the two scenarios, normalized by the slight difference in the total car production, is approximately $ 285,000 in a year. It is interesting to notice that producing on two shifts lowers the consumption of natural gas, relative to electricity. It would be more suitable in places with a lower cost of electricity, to save on the vehicle production cost.

Table 4.10 – Scenario 2 results overview

	Energy	Cost
Electricity, total	43,010 MWh	$ 2,640,804
Natural gas, total	199,369 MWh	$ 2,550,318
Electricity, per car	236.59 kWh	$ 14.53
Natural gas, per car	1,096.70 kWh	$ 14.03

In Figure 4.7 the electrical consumption is reported, for each sub-process, every month. The "shape" of the diagram is very similar to the previous scenario, with a less pronounced peak and valley in July and August because of shifting of the vacation downtime earlier, that affects equally July and August. All the considerations for the previous scenario are still valid. The load of the powder booth, decks and rework, inspection and technical booths has become slightly larger in the "booths family", because of the deactivation of the color booth #1, which accounted for more than a third of the electrical energy of the color booths.

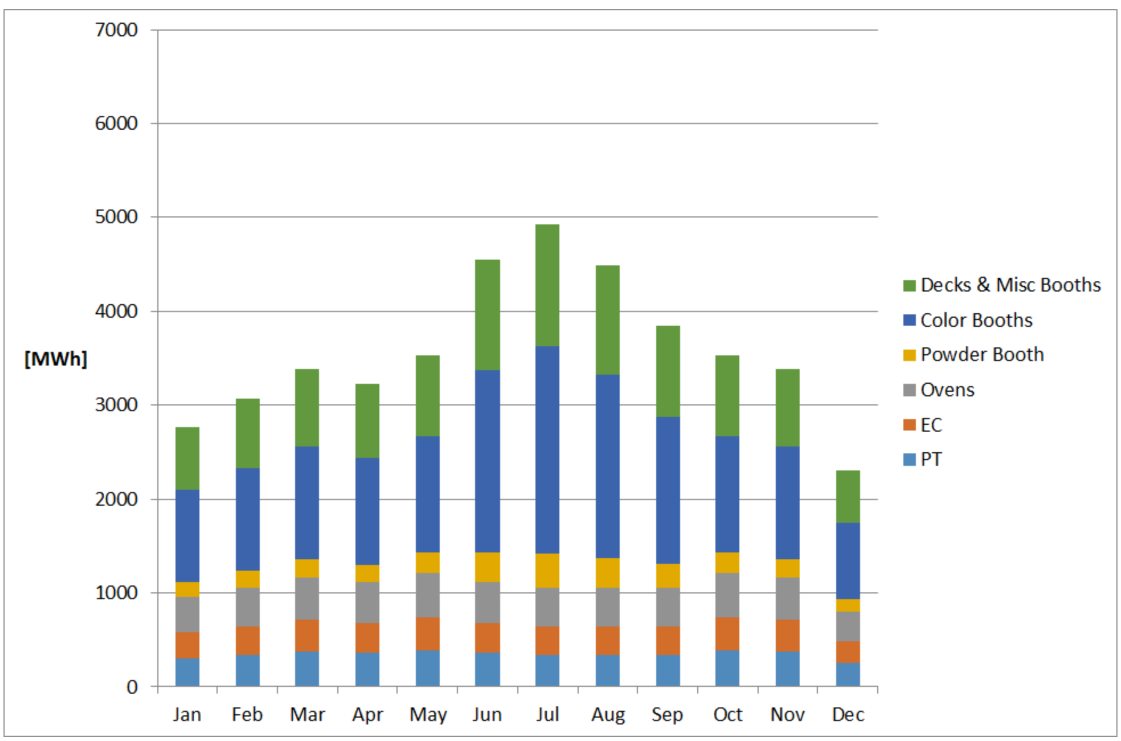

Figure 4.7 – Monthly electric consumption for Scenario 2

Natural gas consumption, whose monthly trend is reported in Figure 4.8, is analogous to the previous scenario. The ovens' natural gas consumption is constant throughout the year, being less sensitive to the external temperature, and the contribution of the color booths has decreased compared to Scenario 1.

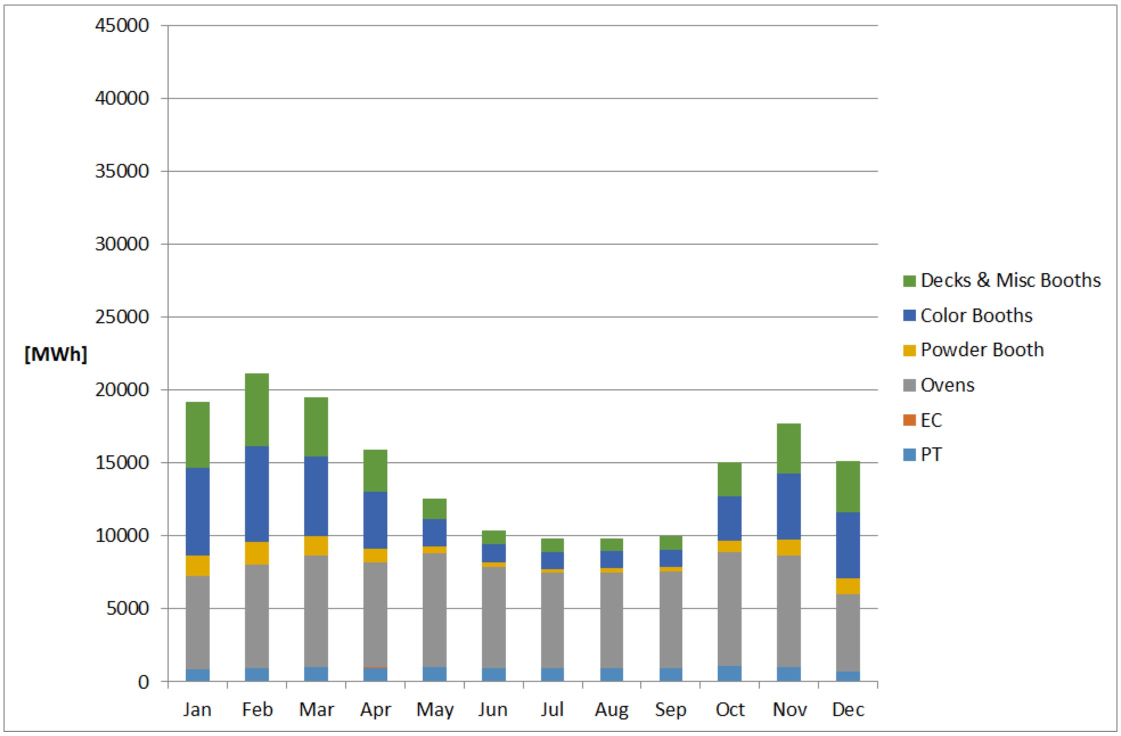

Figure 4.8 – Monthly natural gas consumption for Scenario 2

The contribution of each sub-process to the energy cost is reported in Figure 4.9. The ovens' contribution has lowered, while that of pretreatment and the booths have risen slightly. The color booths' share of the energy cost, apparently in disagreement with the previous discussion, is almost the same as the previous scenario. This is because there are two factors that affect the energy consumption: asset utilization and active lines. The benefit of deactivating a line, decreasing the absolute power consumption of the color booths, and the increase of the utilization of the two booths that are still active, since the production rate is only slightly lower than the maximum capacity of the two booths in parallel, is balanced by the increase of production time and the shift of the vacation downtime.

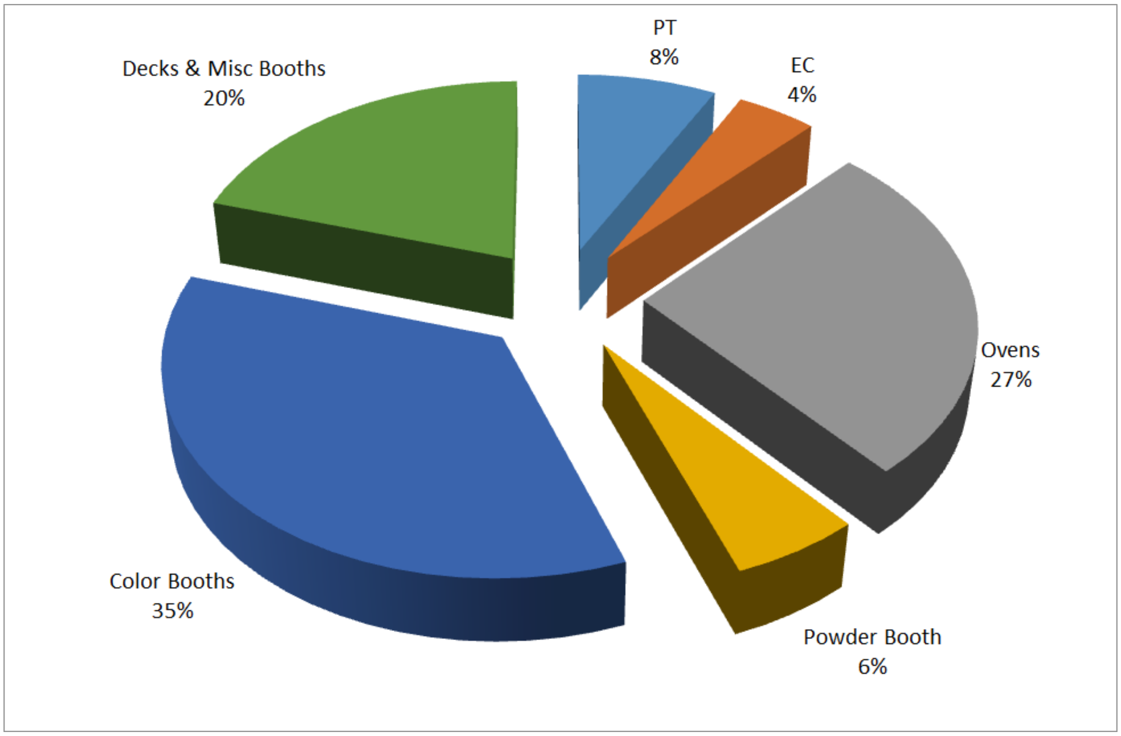

Figure 4.9 – Energy cost proportion per sub-process for Scenario 2

The charts in Figure 4.10 and Figure 4.11 show the relative proportions of the energy consumption of each sub-process in the paint shop. The effect on the booths and on the ovens of the variability of the external temperature is clearly visible, for both the electrical and the natural gas consumption. The trend for the monthly unit energy cost for a year, drawn in Figure 4.12, is similar to the one obtained for Scenario 1, with a minimum in May and another in October.

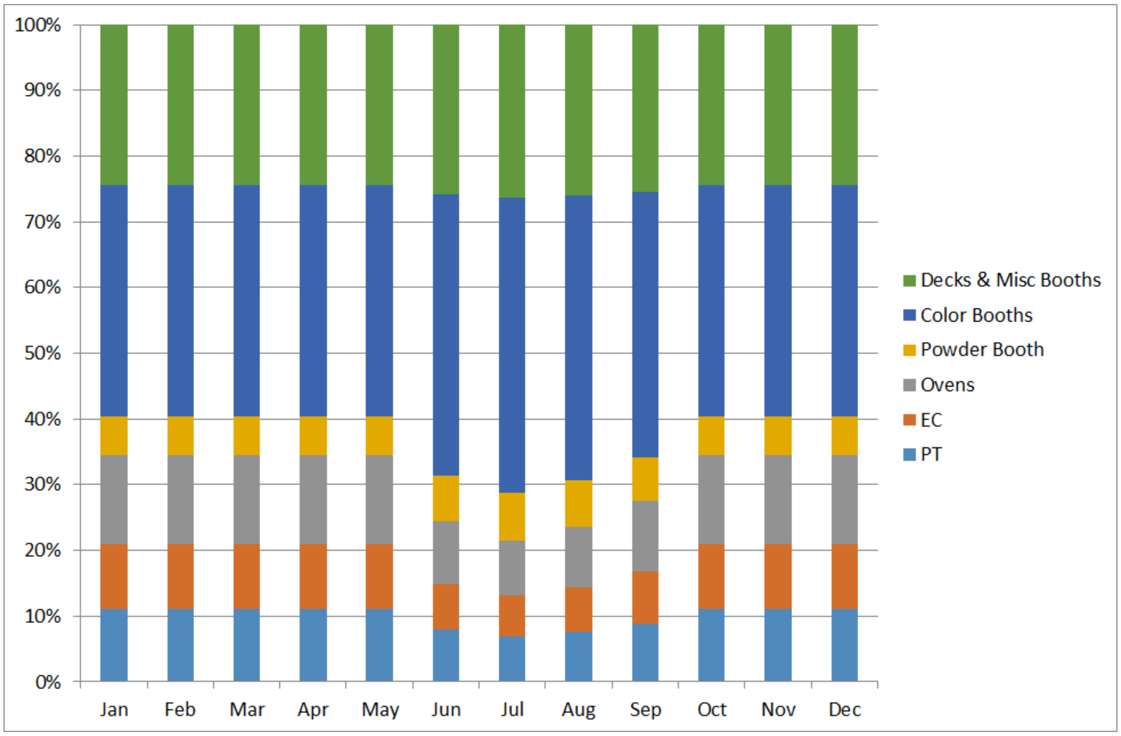

Figure 4.10 – Monthly electric energy share within paint shop for Scenario 2

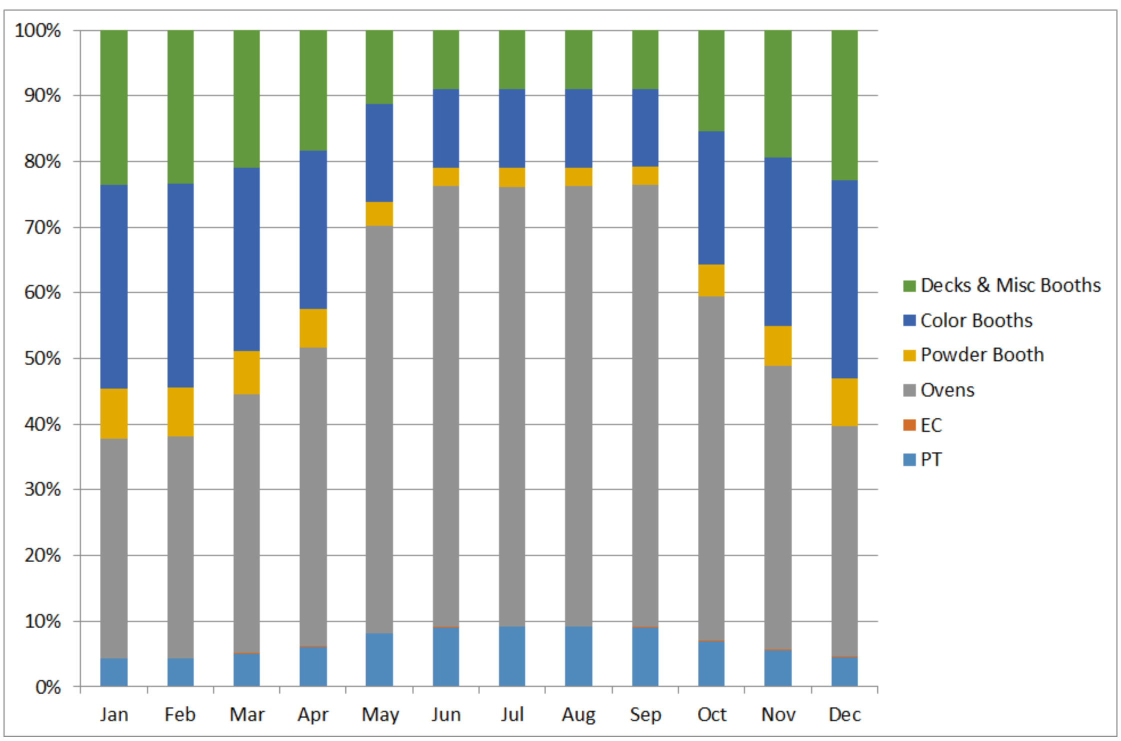

Figure 4.11 – Monthly natural gas energy share within paint shop for Scenario 2

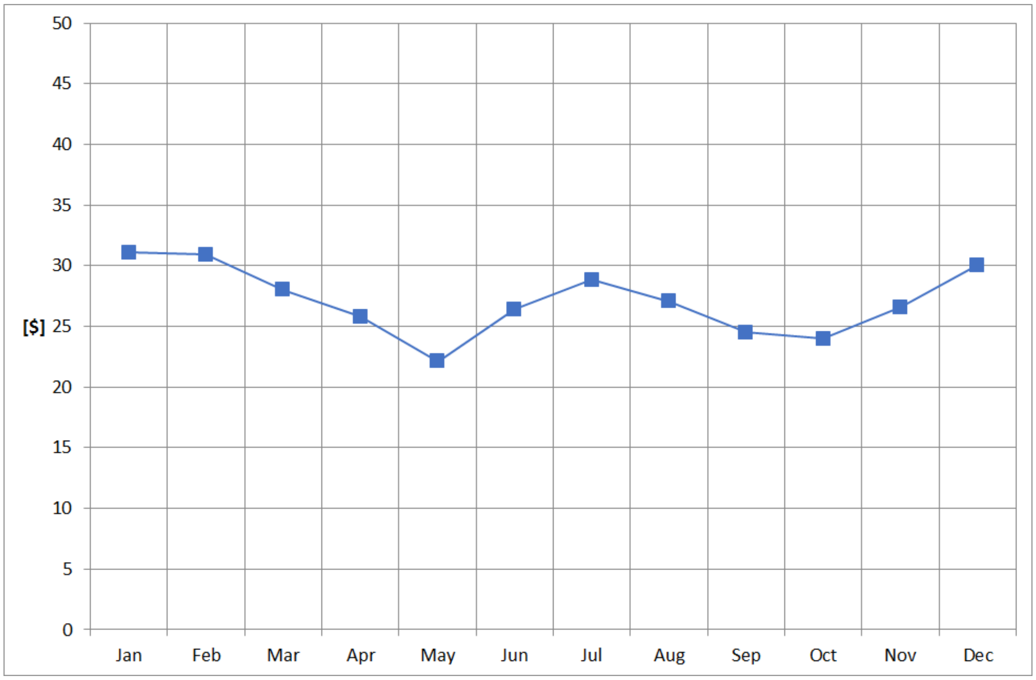

Figure 4.12 – Unit cost throughout a year for Scenario 2

4.2.3 Scenario 3

Scenario 3 was a modification of Scenario 1, with no shutdown during the weekend. Its result should give an idea of the impact of having the equipment running in the days in which production is null, and of avoiding start-up phases at the beginning of the production period. An overview of the consumption data is reported in Table 4.11. The first thing that can be noticed is that the average cost per unit has increased substantially, by approximately $ 10 per unit – in comparison with Scenario 1. The running cost for the paint shop, in a year, has risen by $ 2 million, value that is significant in the plant budget. It is interesting to see that the electricity and natural gas usage have also increased by the same relative amount.

Table 4.11 – Scenario 3 results overview

	Energy	Cost
Electricity, total	59,369 MWh	$ 3,645,266
Natural gas, total	302,569 MWh	$ 3,870,449
Electricity, per car	327.46 kWh	$ 20.11
Natural gas, per car	1,668.88 kWh	$ 21.35

The electrical consumption is plotted by month in Figure 4.13. It follows the trend of Scenario 1, with a uniform upward shift of approximately 1 GWh per month. The natural gas consumption is depicted in Figure 4.14. In both the diagrams it is possible to notice that the difference between summer and winter months is amplified relative to Scenario 1. This is because the systems are running also during the weekend, and they are subjected to the external conditions for, on average, 8 more days per month.

The relative contribution of each sub-process does not change relative to the scenario with shutdown during the weekend. This is confirmed in Figure 4.15, in which the energy cost share is reported. The most significant result of keeping the systems running in the days in which no vehicle is produced is a uniform increase of the energy involved in the painting process, with relative proportions not affected. Although Scenario 1 is affected by the additional consumption due to the start-up operations every Monday, shutting the systems down on the weekend appears to be still the best solution for energy savings.

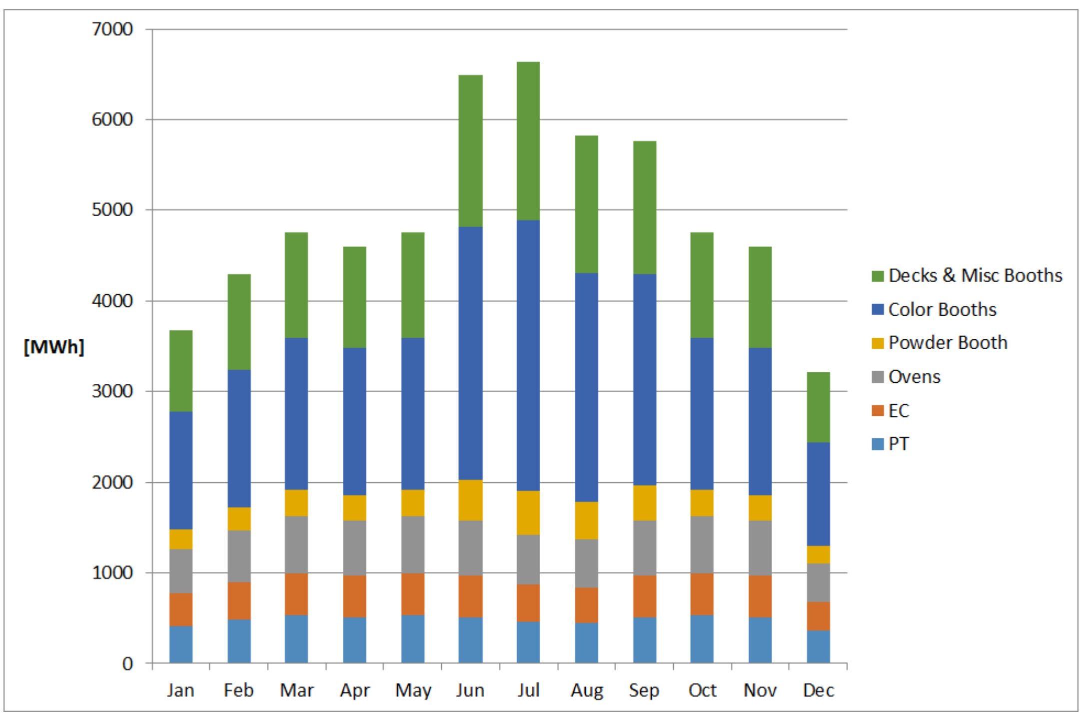

Figure 4.13 – Monthly electric consumption for Scenario 3

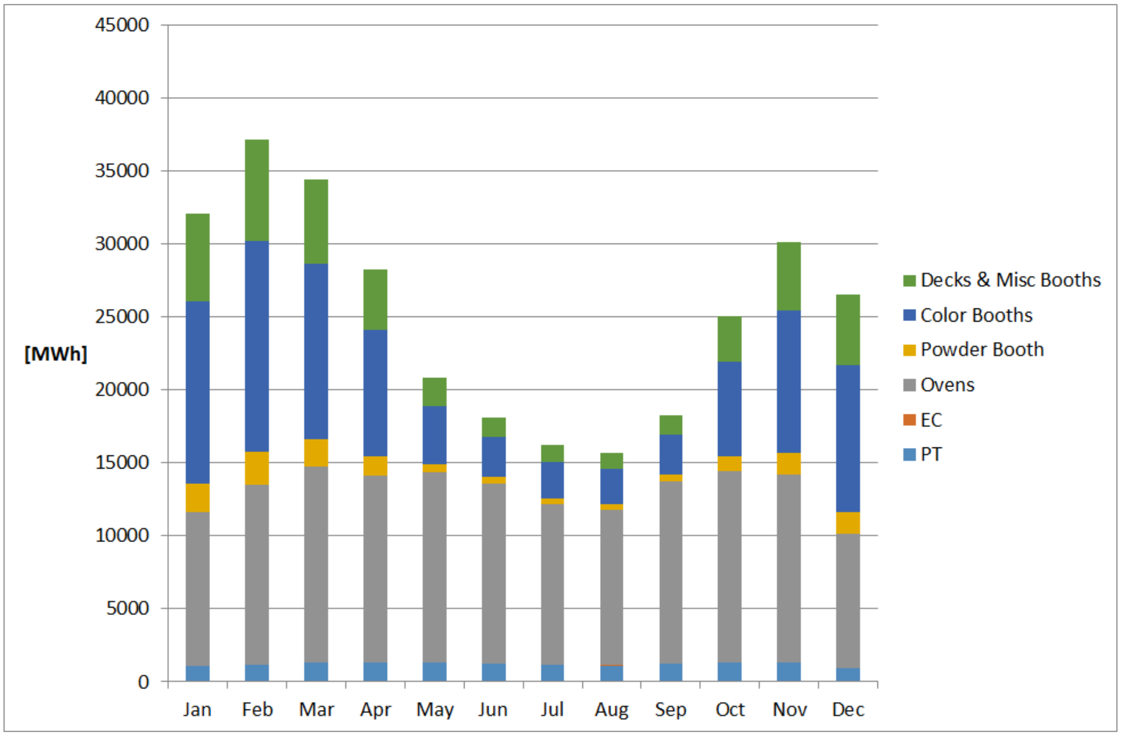

Figure 4.14 – Monthly natural gas consumption for Scenario 3

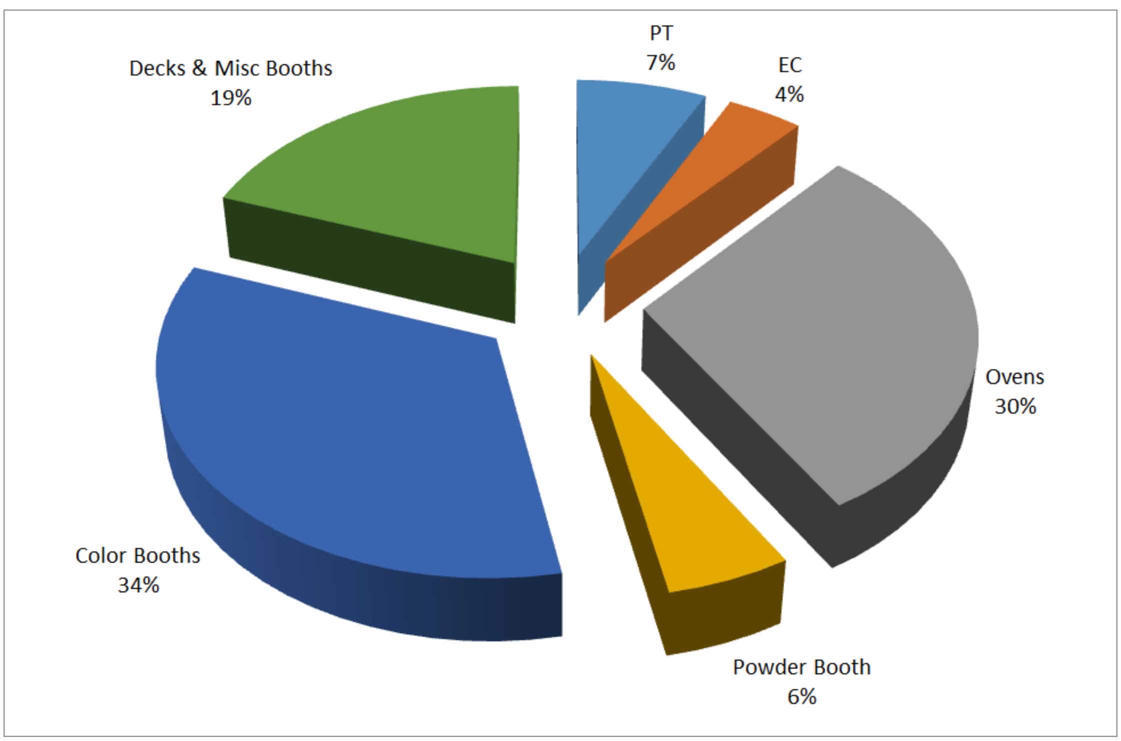

Figure 4.15 – Energy cost proportion per sub-process for Scenario 3

In Figure 4.16 and Figure 4.17 the diagrams of the relative consumption of natural gas and electricity by each sub-process throughout the year do not show considerable changes compared to Scenario 1, on which it is based. The trend of the total cost per unit, instead, changes significantly. As shown in Figure 4.18, the peak that in Scenario 1 was encountered in the central summer months, it has broken down in two minor peaks, with a smaller fluctuation, generated by the vacation schedule. The summer cost per unit is then generally more uniform.

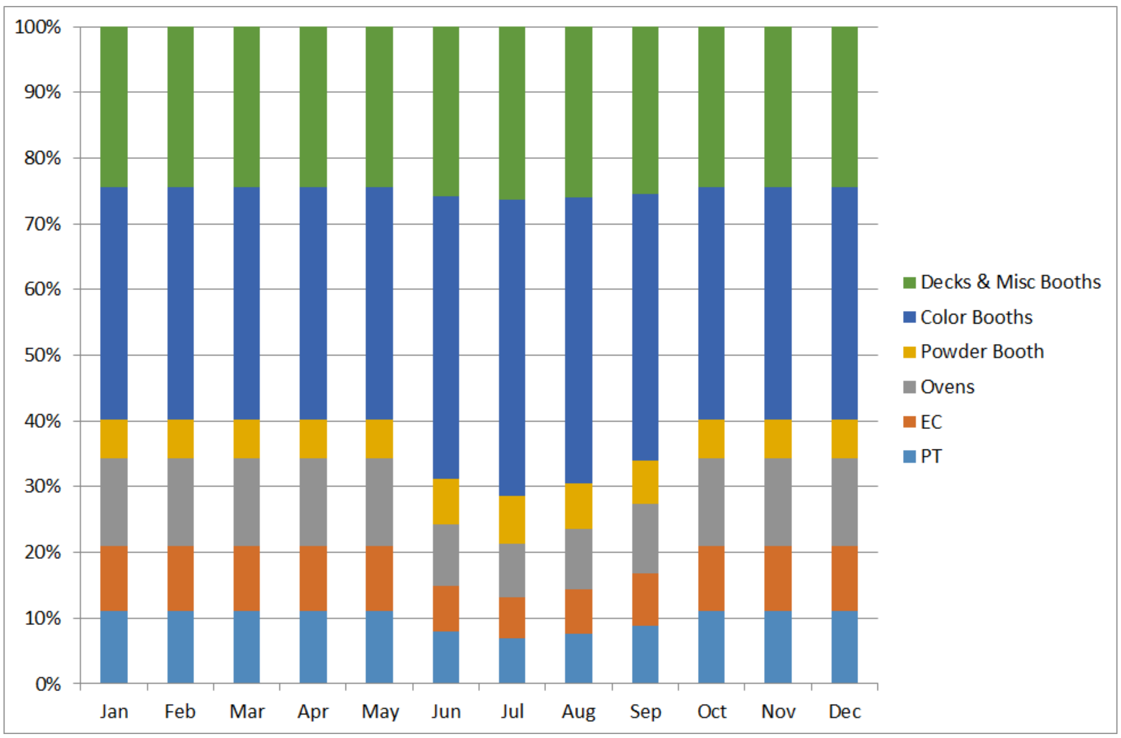

Figure 4.16 – Monthly electric energy share within paint shop for Scenario 3

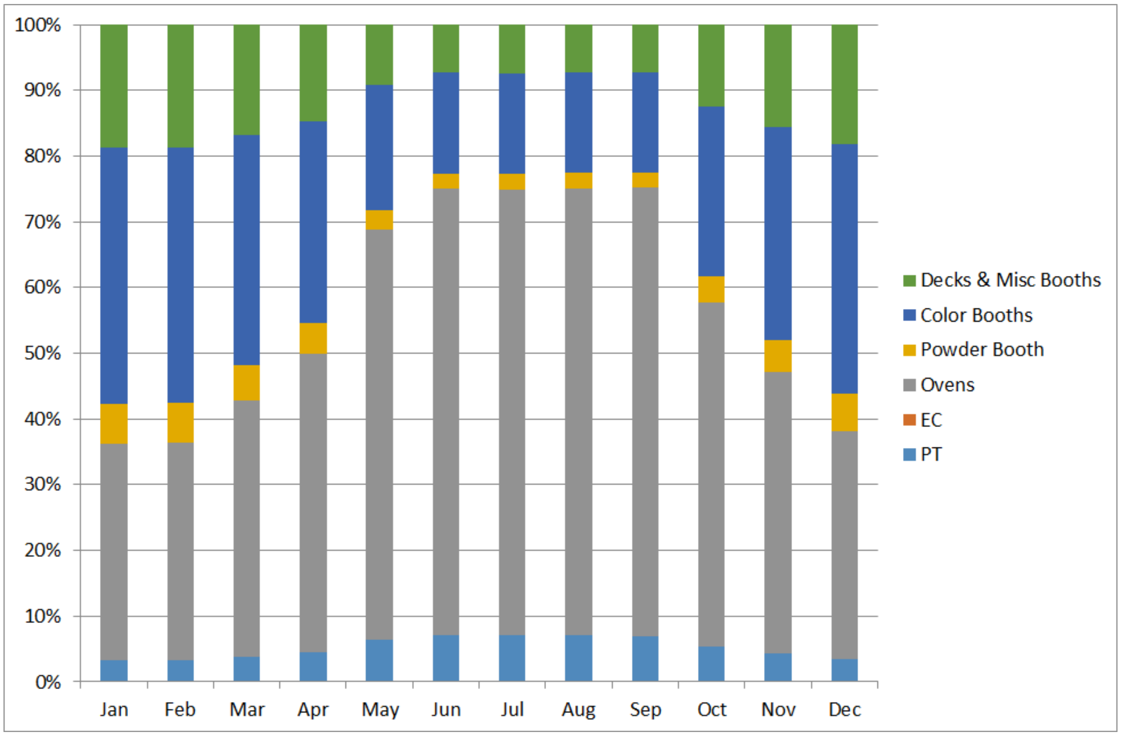

Figure 4.17 – Monthly natural gas share within paint shop for Scenario 3

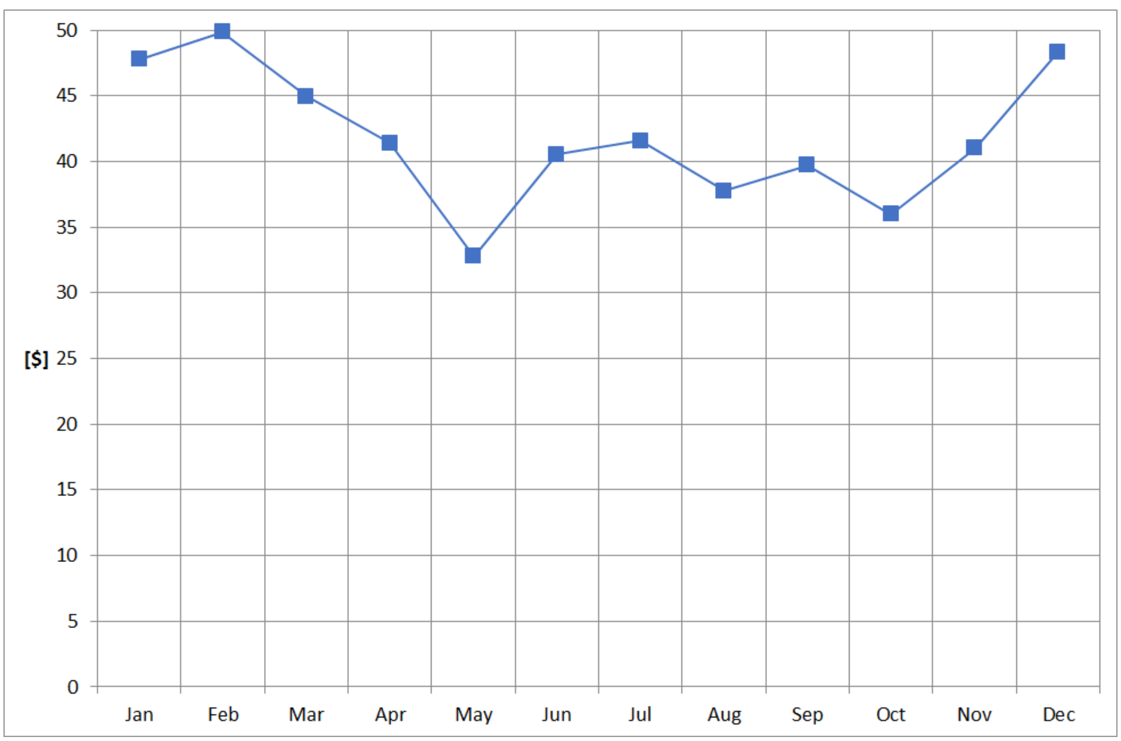

Figure 4.18 – Unit cost throughout a year for Scenario 3

4.2.4 Scenario 4

Scenario 4 was a modification of scenario 2. The plant is operative during the weekend, and no start-up operation was required at the beginning of the week. The scenario on which it is based had similar results to the one on which Scenario 3 was built; therefore, almost the same cost per unit as Scenario 3 was expected. Table 4.12 confirms the prediction. It is important to remark that a small saving on the production of a car could result in a considerable amount of money that is available for the company, because of the high numbers that characterize today's mass production.

The total energy cost per unit of the vehicles painted with scenario 4 production schedule averages at $39 per car. It is approximately two dollars cheaper than Scenario 3, and this situation reflects the effect of longer daily production.

Table 4.12 – Scenario 4 results overview

	Energy	Cost
Electricity, total	59,369 MWh	$ 3,645,266
Natural gas, total	274,448 MWh	$ 3,510,733
Electricity, per car	326.58 kWh	$ 20.05
Natural gas, per car	1,509.70 kWh	$ 19.31

Figure 4.19 and Figure 4.20 show the same trend as Scenario 2, with a constant upward shift of 1 GWh for the electrical consumption. As in the previous case, the fluctuations given by the external temperature variation are amplified, and the proportions among the sub-processes are the same as in Scenario 2. As a confirmation, the chart in Figure 4.21 is identical to the diagram in Figure 4.9.

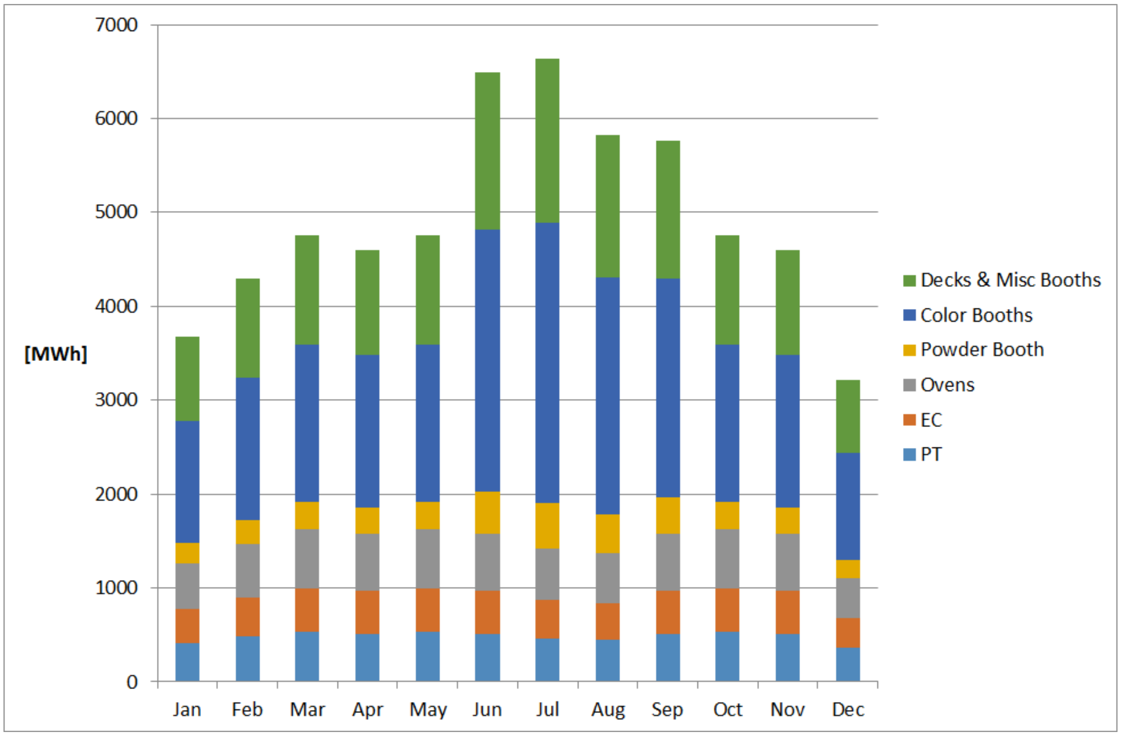

Figure 4.19 – Monthly electric consumption for Scenario 4

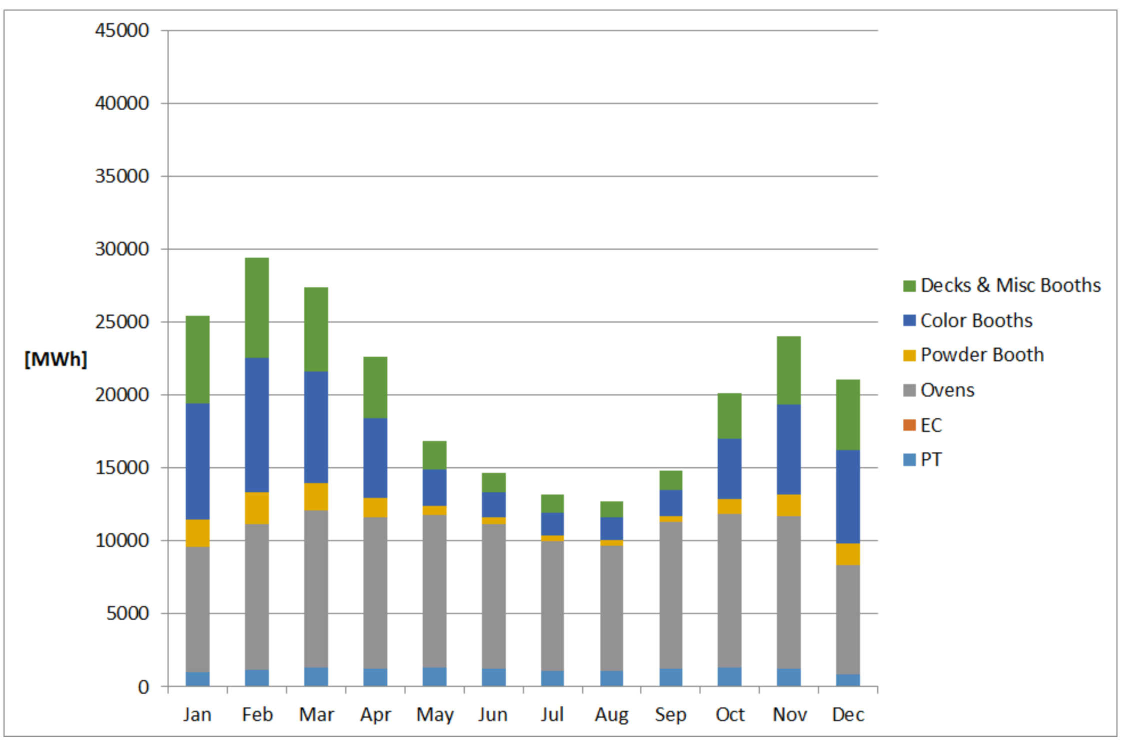

Figure 4.20 – Monthly natural gas consumption for Scenario 4

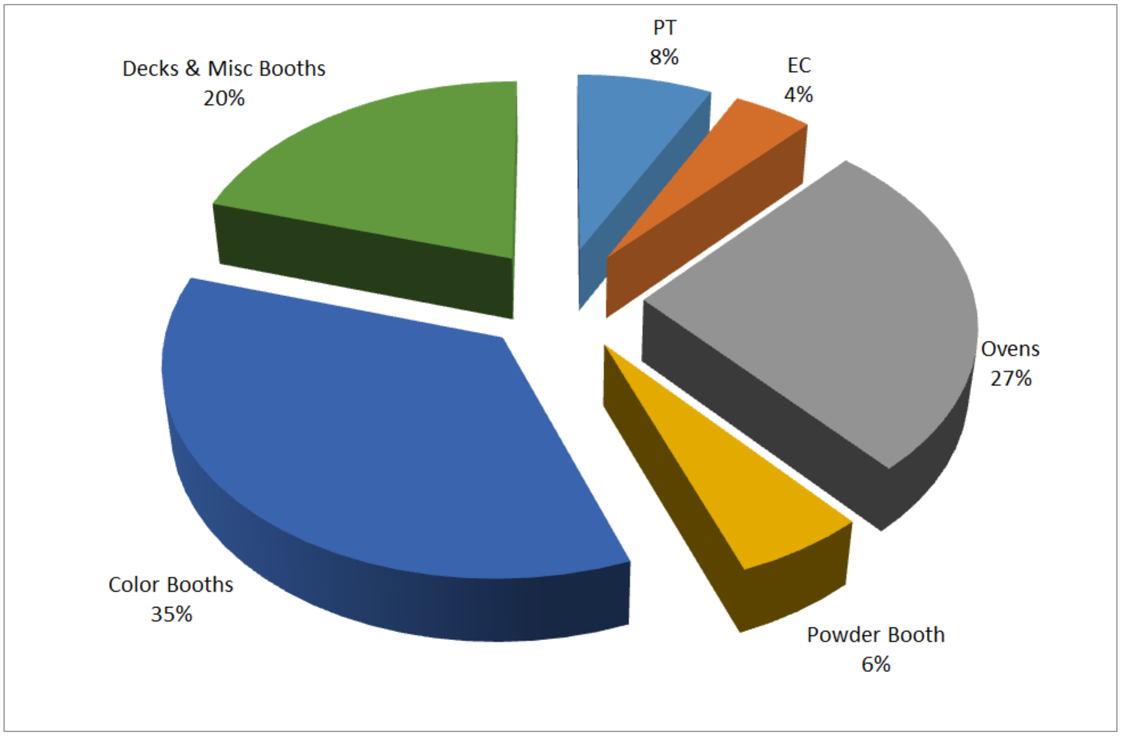

Figure 4.21 – Energy cost proportion per sub-process for Scenario 4

The considerations that have been made in the previous section, for Scenario 3, are still valid. The diagrams in Figure 4.22 and Figure 4.23, show the trend of the relative amount of energy spent by each sub-process along a year, while the trend of the total cost per unit in Figure 4.24 shows the same behavior as Figure 4.18.

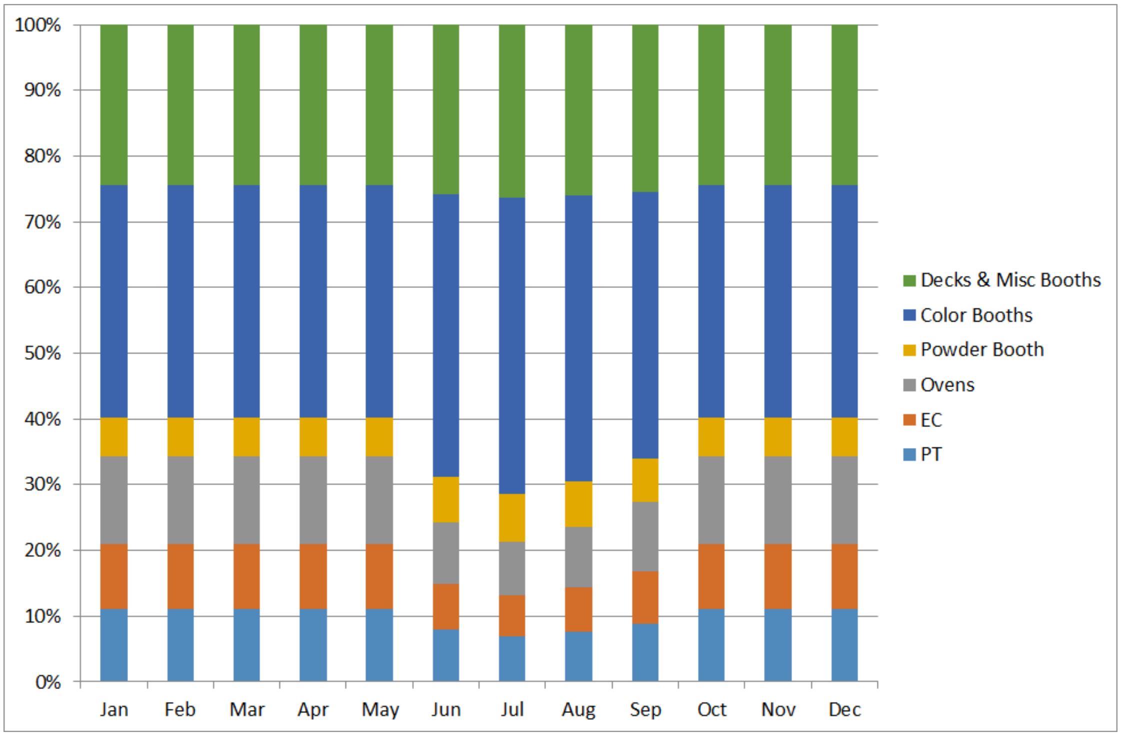

Figure 4.22 – Monthly electric energy share within paint shop for Scenario 4

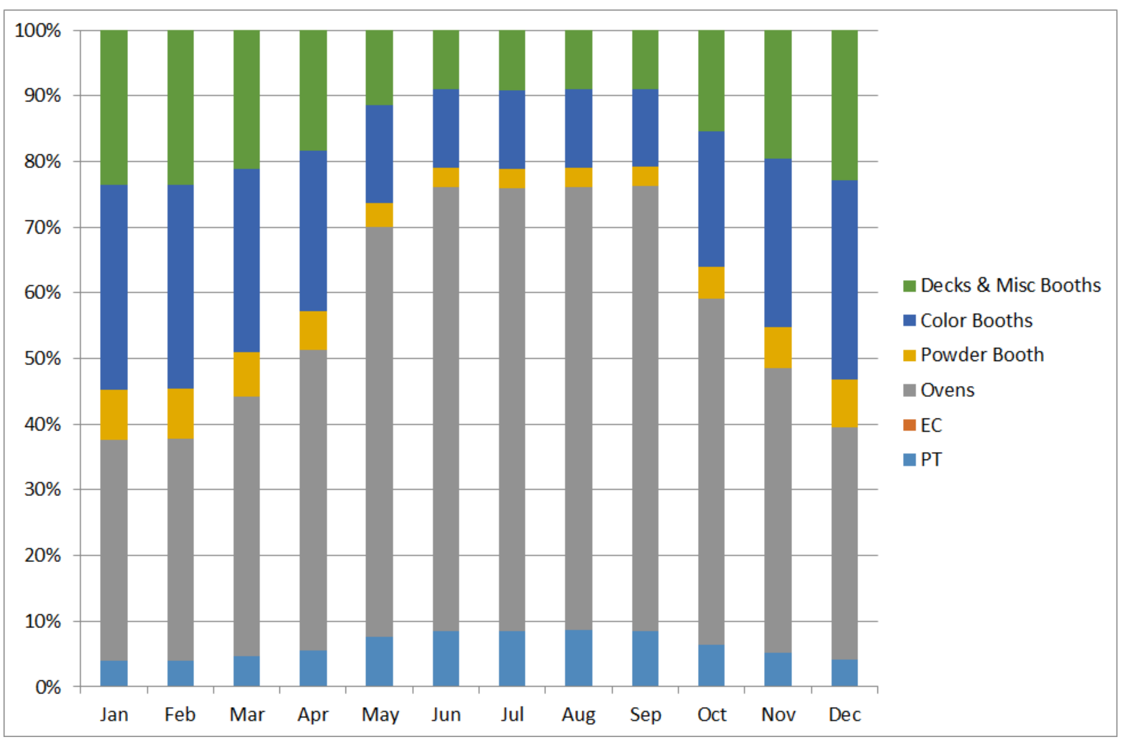

Figure 4.23 – Monthly natural gas share within paint shop for Scenario 4

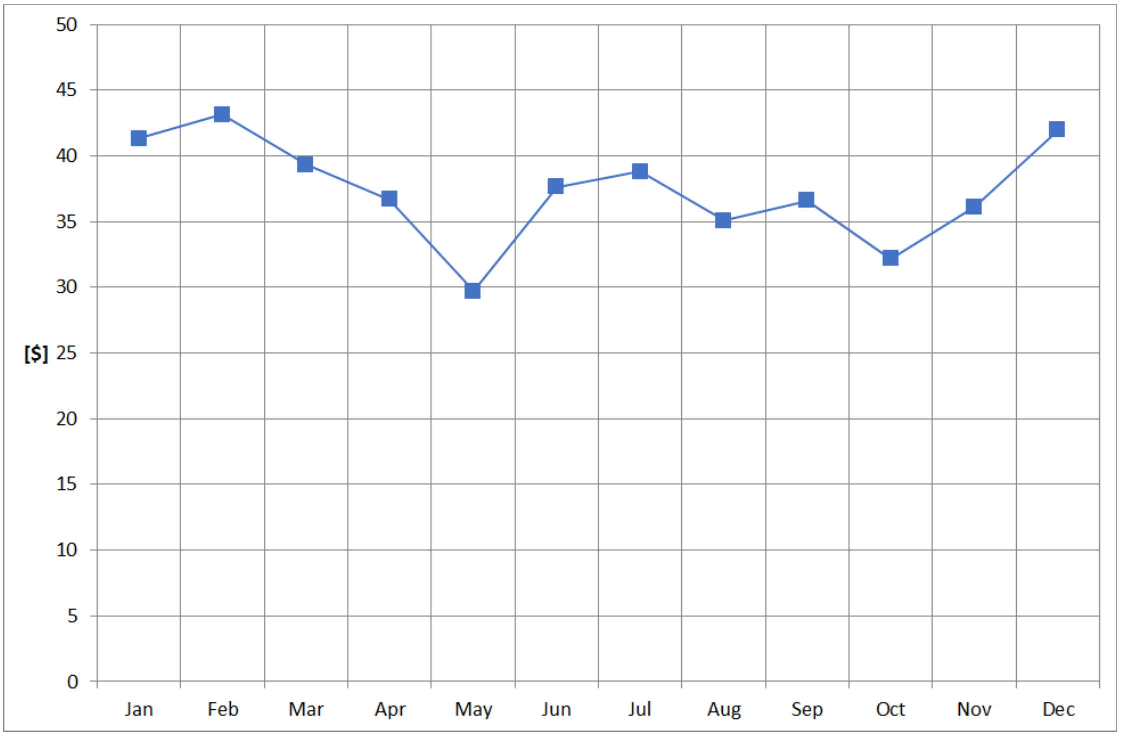

Figure 4.24 – Unit cost throughout a year for Scenario 4

4.2.5 Scenario 5

The fifth scenario was completely different. It was conceived to optimize the asset utilization, and to have no time in which the equipment is running without painting cars. As already discussed, it is not a feasible and realistic scenario, but it can be analyzed to understand the amount of losses due to the production schedule for a plant like the SHAP, and to get a measure of the difference. In Table 4.13 the results of this strategy are reported. The total production is 180,000 units per year, and the total painting energy cost per unit is slightly higher than $14. The cost per unit has then been cut to half of the best production strategy among Scenarios 1 to 4. In a year, approximately $2.5 million would be saved. Naturally, this result hides the real cost of this strategic plan: inventory and other logistic expenses, unavoidable in case of a production schedule of this kind, could be higher than the saved amount.

Table 4.13 – Scenario 5 results overview

	Energy	**Cost**
Electricity, total	15,330 MWh	$ 941,285
Natural gas, total	125,778 MWh	$ 1,608,955
Electricity, per car	85.17 kWh	$ 5.23
Natural gas, per car	698.77 kWh	$ 8.94

Since the systems are operative just for three full months, the diagrams in Figure 4.25 and Figure 4.26 do not carry much useful information. The chart in Figure 4.27 shows the energy share of each sub-process, and at first glance it is possible to notice that it is very close to the one generated by the scenarios in which the production is organized in 2 shifts, with slightly lower oven energy consumption and slightly higher booth energy use. This information, deprived of the context and the boundary conditions, could lead to a misinterpretation: actually, Scenario 5 is organized in such a way so as to complete the production in the months of December to March. As already discussed, in the case of low outside temperature, the oven natural gas consumption does not change significantly, while the booths natural gas consumption increases dramatically. Using this production strategy, the comparison has to be performed just on the months in which the two schedules overlap.

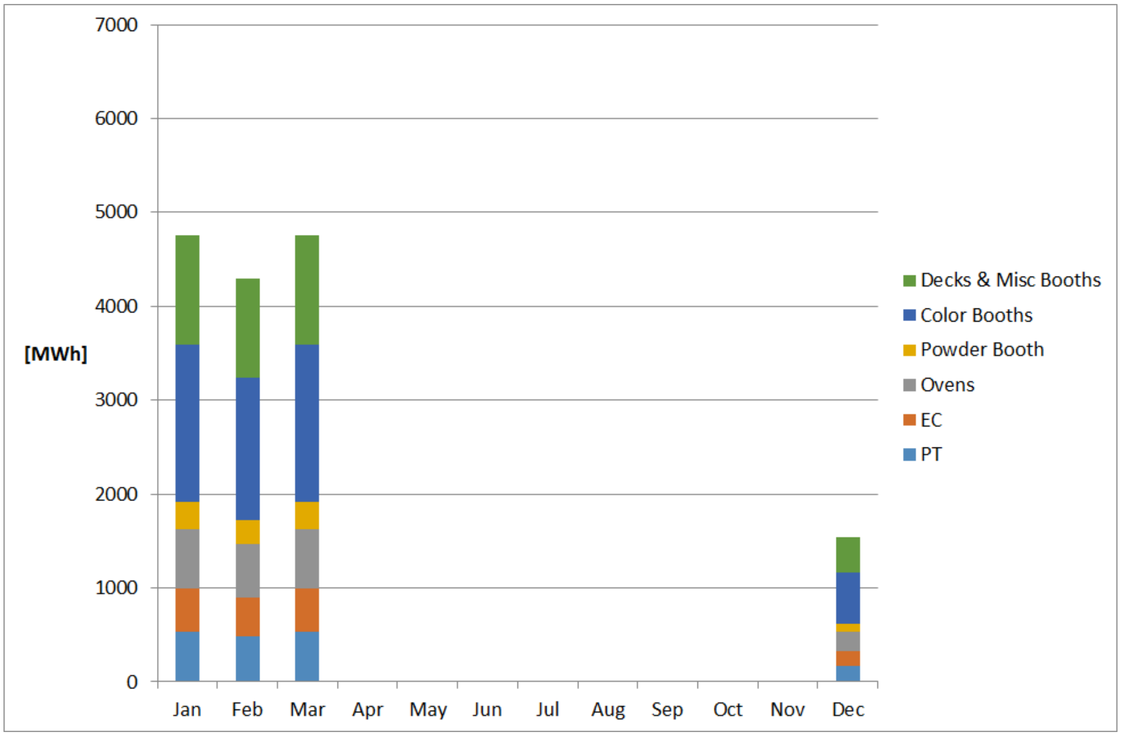

Figure 4.25 – Monthly electric energy consumption for Scenario 5

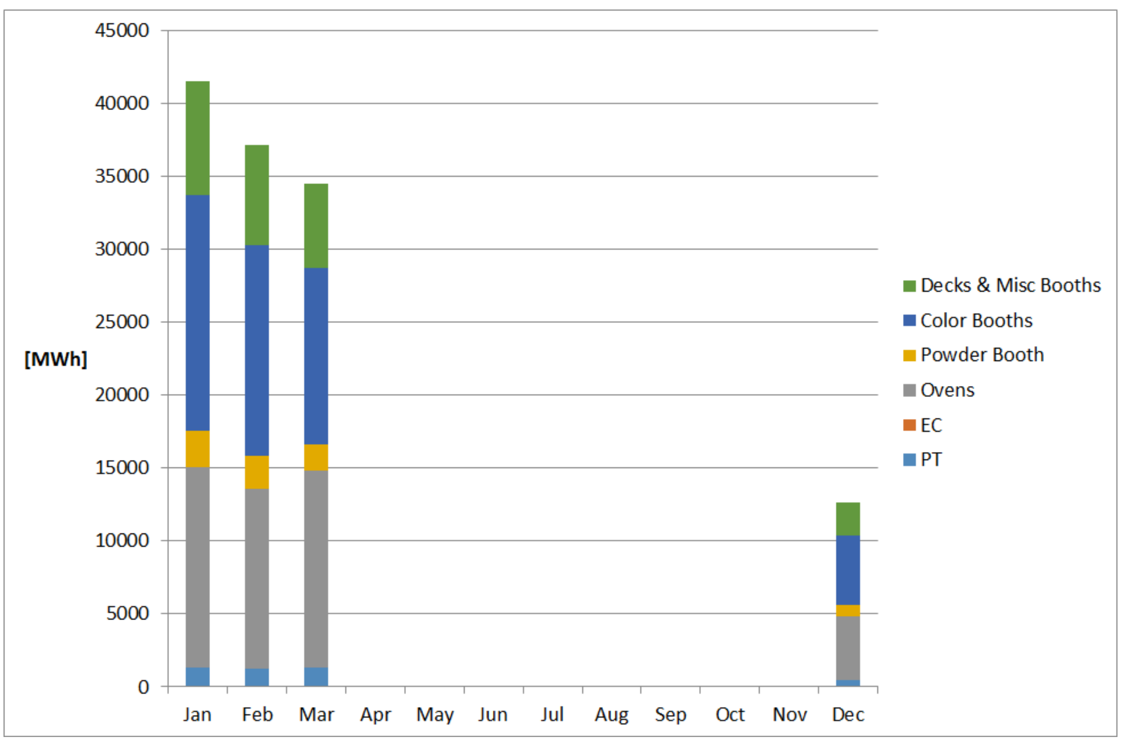

Figure 4.26 – Monthly natural gas consumption for Scenario 5

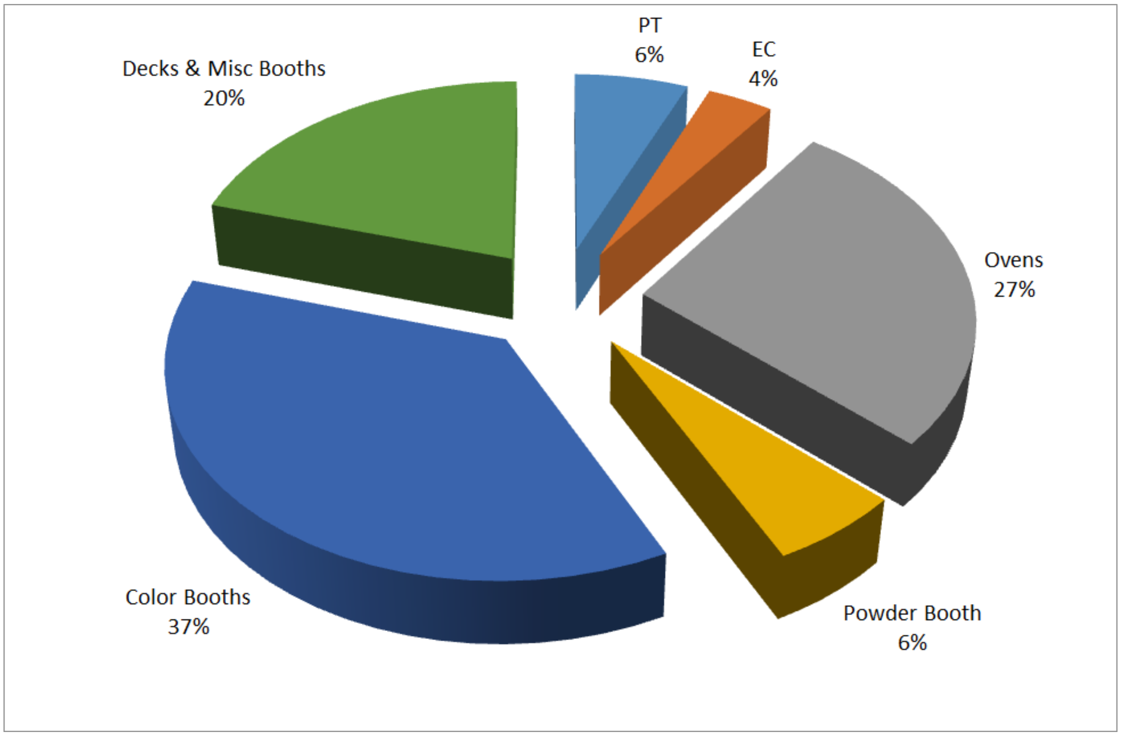

Figure 4.27 – Energy cost proportion per sub-process for Scenario 5

Figure 4.28 and Figure 4.29 contain the diagrams of the trend of the relative energy consumption for each process. Throughout the four months in which vehicles are produced, electrical energy shows a constant behavior, while natural gas starts to change due to the milder outside temperature typical of March. The total cost per unit, plotted in Figure 4.30, has not enough time to fluctuate, but shows a minimum for the month of March.

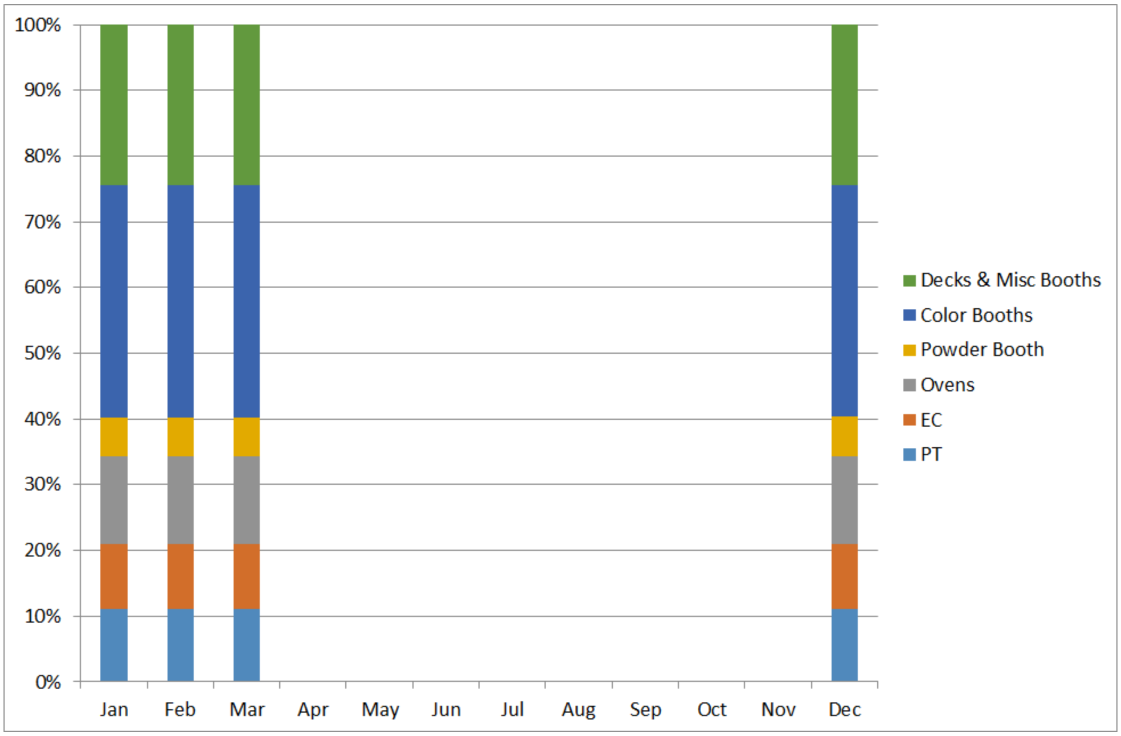

Figure 4.28 – Monthly electric energy share within paint shop

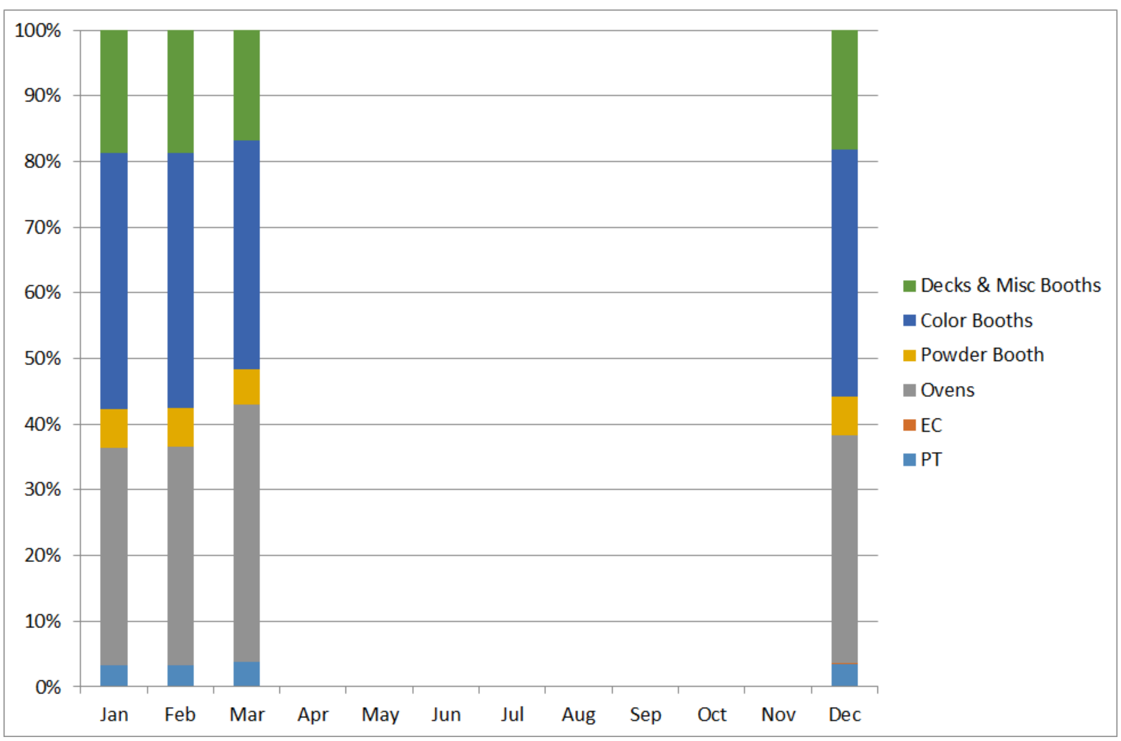

Figure 4.29 – Monthly natural gas share within paint shop

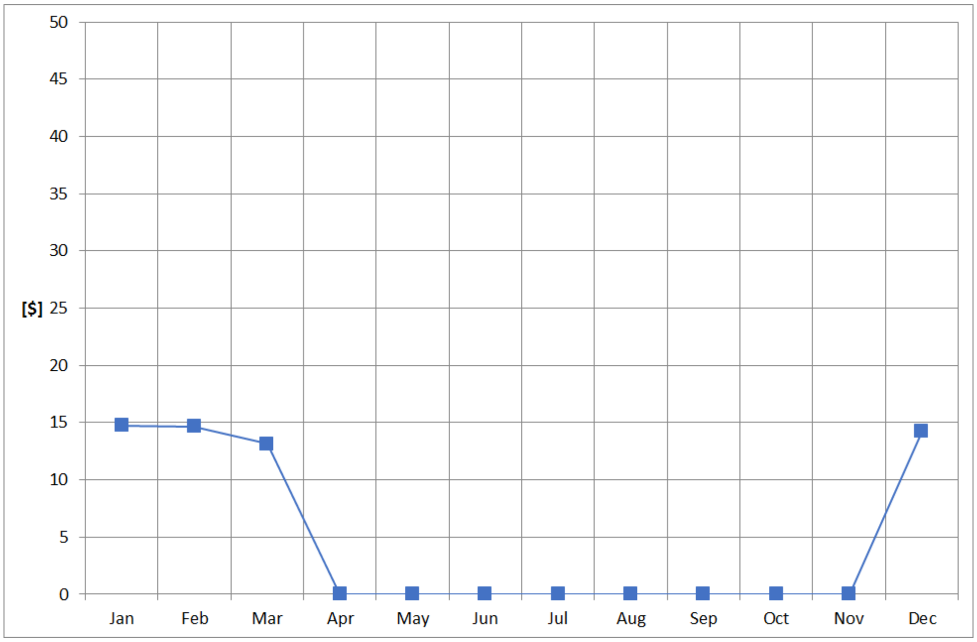

Figure 4.30 – Unit cost throughout a year

4.3 General considerations

Table 4.14 – Results' summary

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Production	181,300	181,790	181,300	181,790	180,000
Unit cost	$ 30.13	$ 28.56	$ 41.46	$ 39.36	$ 14.17
Total expense	$ 5,463,174	$ 5,191,122	$ 7,515,715	$ 7,155,999	$ 2,550,240

From this set of results, we understand that the key for efficiently running an industrial asset is to maximize the utilization time. Especially in the case of a flexible plant, with multiple lines in parallel, trying to spread the production to the largest number of daily hours possible is more important that using the plant at its maximum capacity. Another important aspect to consider is that costs are minimized when, in case of lower-than-maximum production rate and of deactivation of one of the lines in parallel, the remaining lines are exploited near to their capacity limit. Therefore, in a paint shop in which there are three lines for the topcoat, with a capacity of 30 JPH each, if possible the production schedule should be organized in such a way so as to optimize the use of one, two or three lines, keeping them close to 30 JPH.

Booths and decks lights energy use accounts for 1.85% of the total electricity consumption, in the case of Scenario 1. The annual cost relative to only the lights inside the spray booths and the generic booths and decks is then around $ 50,000.

It has been also shown that the start-up operations have an energetic cost that is much lower than keeping the systems running during the night or general production downtime, although not all the energy users in a paint shop were considered in the model. While energetically it could be considered as an advantage to shut all the systems down every time that the lines are not running, it adds logistical expenses that are not in the scope of this work. These costs can be related to:

- manpower: start-up operations have to be carried out before the start of the production, to bring all the process variables at set point conditions before the beginning of the shift. These operations are usually performed or supervised by workers, and this results in an extension of the working hours for a sub-set of the total work force;
- plant operation: as a consequence of the previous point, systems like lighting, HVAC, oxidizers and fixed-consumption equipment have to be operative during start-up, even though they are not directly involved in the procedures;
- quality: as already discussed in the introduction, the coating of a vehicle is one of the main quality indicators that the customer perceives. Therefore, the outcome of the painting process has to respect strict standards and to go through severe inspections. One of the ways to achieve and maintain repeatability, and to obtain a flawless coating is to respect the set points in dip processes, decks, booths, ovens, to prevent incomplete surface covering, paint blistering, gloss and color non-uniformities. Therefore, especially for the most delicate and sensitive processes, a stabilization phase, in which the parameters that control the production are carefully monitored is necessary;

- protocols: a start-up operation usually means following a written procedure, conceived to minimize the probability of a human mistake, that can be complex and time-consuming.

However, while production strategies that use one or two shifts per day are almost equivalent, when it comes to achieve a production target at the end of the year, scenario 5 shows that there could be an improvement made, but solutions need to be possible and enlightened. Although the cost savings per unit does not seem excessive, a small improvement, on a large scale, can make a large difference.

The results, that show that the energy consumption is approximately 200 – 300 kWh of electricity and 1 – 1.5 MWh of natural gas per car are in line with the literature [15], [6], [4], [7], [25], [12]. The suggested values, a result of the numerous studies on the subject, are slightly higher, due to the choice of not considering some areas in the model. Moreover, SHAP paint shop is a very modern and modular plant, which was conceived in the early 2010s, while the literature is based on the average of North American and European plants, sometimes with more than 30 years of service.

4.4 Sensitivity analysis

The sensitivity of the model to some parameters has been tested with a sensitivity analysis; input values and some boundary conditions have been changed in a limited range, to evaluate the model robustness and the actual impact of these parameters on the outcome. The parameters that have been studied are:

- dip processes:
    - heat transfer
        - insulation material and thickness
        - waterside fluid velocity
        - wall external temperature
- fans:
    - efficiency
    - pressure drop

- ovens:
    - heat transfer
        - insulation material and thickness
        - inside air velocity
        - wall external temperature
- color booths:
    - set point.

The sensitivity analysis has been performed comparing the variation of a parameter with its effects on the power consumption of the equipment that is directly affected by its value and on the unit energy cost running Scenario 1. The parameters have been varied according to their physical characteristics, avoiding extreme changes that would not be obtainable in the real world.

4.4.1 Dip processes

4.4.1.1 Insulation material and thickness

The heat transfer through the tank walls depends on many parameters. One of the most important ones is the insulant properties, the conductivity *k* and the thickness *t*. Table 4.15 reports the values of these properties, valid for each tank in the model. Varying thickness and conductivity of the insulation layer, causing a variation in the heat exchange, and consequently in the natural gas consumption is expected. As shown in Table 4.16, both the conductivity and the thickness were varied by an increment and a decrement of 20%. The effect of these two modifications on the instantaneous power that has to be delivered to the bath and on the total energy cost per coated vehicle have been then separately accounted, to verify the sensitivity of the model to these parameters. The resulting variation of the instantaneous power for both the parameters was significant but low. Moreover, as expected, to reduce the energy consumption, the material is slightly more important than the layer thickness. This is due to the position of each factor in the ratio for the conductive heat transfer coefficient – the thickness is in the denominator.

Table 4.15 – Original values for insulation layer

Insulant k [W/m·K]	0.04
Insulant thickness [mm]	50.80
Power consumption (kW)	1780.47
Unit cost ($)	30.21

Table 4.16 – Parameters variation

Parameter	Variation	Power Consumption	Unit Cost	Significant?
Insulant k	+20%	+3.3%	+0.2%	no
	-20%	-3.6%	-0.21%	no
Insulant t	+20%	-3.4%	-0.2%	no
	-20%	+3.8%	+0.22%	no

4.4.1.2 Waterside average fluid velocity and wall external temperature

As already discussed, the heat transfer through the dip tank walls depends mainly on the insulation. Since the internal and external heat transfer coefficients are considerably higher than the one that is given by the insulant, and the total heat transfer coefficient is obtained by the inverse of the sum of the thermal resistances in series, the dominant factor is the resistance of the wall. The water average speed influences the waterside heat transfer coefficient, while the temperature difference between external wall and the plant air influences the airside heat transfer coefficient. The original values are shown in Table 4.17. The outcome of the model is expected to be not sensitive to the variables that can influence the waterside and airside heat transfer coefficients. This expectation was confirmed as shown in Table 4.18.

Table 4.17 – Original values for fluid velocity and wall temperature

Average speed [m/s]	0.1
ΔT [K]	5.55
Power consumption (kW)	1780.47
Unit cost ($)	30.21

Table 4.18 – Parameters variation

Parameter	Variation	Power Consumption	Unit Cost	Significant?
Average Speed	+20%	+0.09%	+0.005%	no
	-20%	-0.2%	-0.01%	no
ΔT	+100%	+2.3%	+0.13%	no
	-50%	-2.8%	-0.16%	no

4.4.2 Ovens

4.4.2.1 Insulation material and thickness

As for the dip processes, the heat transfer through the walls of the ovens depends mainly on the insulation layer characteristics. The sensitivity analysis has been performed in the same way, but because of the variability induced by the weather it has not been possible to analyze the variation of the instantaneous power; instead, the total energy delivered to the ovens has been evaluated. In Table 4.19 the insulation layer properties are reported, and in Table 4.20 it is possible to notice that the variations in the ovens' consumptions are similar to the ones experienced in the dip processes. However, since the ovens account for the 30% of the total energy of the paint shop, the variations in the ovens insulation layer affect more the final unit cost than in the previous case. It is possible to say that the energy cost per unit produced is not very sensitive to the ovens insulation layer properties, but more sensitive than in the case of the dip tanks.

Table 4.19 – Original values for oven insulation layer

Insulant k [W/m·K]	0.04
Insulant thickness [mm]	76.20
Ovens consumption (GWh)	109.094
Unit cost ($)	30.21

Table 4.20 – Parameters variation

Parameter	Variation	Ovens Consumption	Unit Cost	Significant?
Insulant k	+20%	+4.7%	+1.41%	no
	-20%	-5.1%	-1.53%	no
Insulant t	+20%	-2.4%	-0.72%	no
	-20%	+3.2%	+0.96%	no

4.4.2.2 Inside air velocity and walls external temperature

The same considerations that have been made for the dip tanks are valid for the ovens. The energy consumption of the ovens is not expected to be very sensitive to the parameters that influence the inside and outside heat transfer coefficients. A sensitivity analysis has then been performed on the two terms that most influence the outcome. These values, analogous to the ones that have been tested in Section 4.4.1, are the air velocity on the inside wall surfaces and the outside wall temperature difference. The range of variation is relatively high, due to the high uncertainty that characterizes the two parameters; as expected, the model outcome shows a low sensitivity to the variation of these terms, as shown in Table 4.22. This suggests that the ovens' energy consumption, despite the uncertainty embedded in some estimations, can be trusted as reliable.

Table 4.21 – Original values for air velocity and wall temperature

Average speed [m/s]	0.6
ΔT [K]	53.3
Ovens consumption (GWh)	109.094
Unit cost ($)	30.21

Table 4.22 – Parameters variation

Parameter	Variation	Ovens Consumption	Unit Cost	Significant?
Average Speed	+100%	+2%	+0.61%	no
	-50%	-2.5%	-0.75%	no
ΔT	+50%	+0.24%	+0.07%	no
	-50%	-0.4%	-0.12%	no

4.4.3 Fans

4.4.3.1 Efficiency and pressure drop

Fans are employed in every unit of the painting process, and their efficiency and pressure drop values are different, depending on the use, location, and type of fan. Therefore, there is not just one value that can be taken and modified. To solve this problem and perform the sensitivity analysis, a factor has simply been multiplied by the efficiency or the pressure drop in each ventilation power computation. However, it is not practical to evaluate the variation of the fans energy consumption alone, since ventilation is required in each sub-process. Consequently, just the sensitivity of the unit cost to the variation of efficiency and pressure drop has been evaluated. The parameter that has been incremented is not the efficiency, because it could lead to a situation in which it would have had grown beyond 100%. The complement of the efficiency, in Table 4.23 referred as efficiency loss, has then been used for the computations. From the results, it is possible to see that the model sensitivity to the efficiency loss is low, while the pressure drop has a much more important role. It is then important to clean the filters periodically, to ensure the lowest pressure drop that must be overcome by the fan motors.

Table 4.23 – Parameters variation

Parameter	Variation	Unit Cost	Significant?
Efficiency loss	+30%	+1.4%	no
	-30%	-1.2%	no
Pressure drop	+30%	+8.2%	yes
	-30%	-7.7%	yes

4.4.4 Color booths

4.4.4.1 Set point temperature

The color booths' natural gas consumption was modeled and evaluated through the ATU module provided by FCA. The paint shop model sends inputs of external temperature, set point temperature and humidity, requested air flow rate, percentage of recirculation and production schedule to the external module, and collects as output the energy given or subtracted to the air flow by the air treatment units. Therefore, the sensitivity of these outputs to the set point temperature has been investigated.

When working with absolute temperature, a problem occurs: the three most used scales – Kelvin, Fahrenheit and Celsius – are not proportional. Specifically, the zero is not at the same temperature. Since a sensitivity analysis is usually performed on relative increments (and decrements) of a parameter, its result would change according to the scale that has been used. To solve this problem, in Sections 4.4.1 and 4.4.2 the parameter that has been varied is the difference between the plant temperature and the inspected one. Since in that case the parameter to be varied was a difference, and not an absolute temperature, the absolute variation of the difference corresponding to the relative variation dictated by the sensitivity analysis was not affected by the position of the zero, and consequently by the scale used.

In this section a new parameter may be introduced: the temperature difference between the booths' set point and the average external temperature. Due to the high seasonal variability typical of Michigan, however, it has been chosen to not pursue this path. The set point temperature, in degrees Celsius, has been instead used and varied for the sensitivity investigation. In Table 4.24 the original values are reported, with the color booths annual consumption in GWh. Table 4.25 shows the effects of the parameter variation. It is clear that the color booths consumption can be described as sensitive to the set point temperature, since the amplitude of its variation is larger than the parameter. The unit cost variation is moderate, because of the effect of the other sub-processes in the paint shop. Formulating coatings with a larger tolerance to different working conditions can be then the key to achieve considerable savings in the expense of coating a car, through minimizing the energy required to treat the airflow that is blown into the paint booths.

Table 4.24 – Original values for color booths temperature

T [°C]	18.33
Color booths consumption (GWh)	82.25
Unit cost ($)	30.21

Table 4.25 – Parameters variation

Parameter	Variation	Color Booths Consumption	Unit Cost	Significant?
T	+10%	+11.24 %	+1.27%	yes
	-10%	-10.61%	-1.20%	yes

5 Conclusions and Recommendations

5.1 Conclusions

This project's main goals were:

- the generation of an analytical model able to compute the energy consumption of a paint shop, allowing the user change parameters and adjust the production schedule to evaluate the system response to his or her inputs;
- the creation of a virtual environment in which the data relative to the equipment installed into a paint shop can be inserted, and the operation of a specific plant, in a specific configuration, can be simulated.

The SHAP paint shop energy model satisfies these needs, with sufficient robustness and precision, as discussed in Sections 4.1 and 4.4, and offers to the company a tool that could help in decisions, although endless work can be done in the future to improve and integrate it. The final goal is the mutual reduction of energy and vehicle manufacturing costs. In general, the complexity of a car manufacturing plant is such that optimal solutions cannot be the result of study of a single area, but they are usually the outcome of an integrated investigation across the major areas of the plant, and it can be important to be able to use a simple tool to evaluate the effect of the changes applied to other zones on the energy consumption of the paint shop.

The values that have been found in the literature, were confirmed by the model results, for both electricity (200-300 kWh/vehicle) and natural gas (1-1.5 MWh/vehicle) consumption. The proportions of the sub-process consumption values reproduce the results of investigations performed by the authors discussed in the literature review of this thesis.

From the results of the scenarios, it can be noticed that it is possible to reduce the energy consumption of a paint shop simply by managing the production schedule. With continuous production for 4 months and 8 months shutdown, savings of 50% on the unit cost can be achieved. Moreover, analyzing the unit cost trend throughout a year it is possible to identify the spring and the fall as the periods in which the energy cost for the vehicles coating is minimized. Naturally, this result is valid specifically for Sterling Heights climate data. As obtained with

Scenarios 1 to 4, realistic variations of the production schedule, consisting of working shifts arrangement and vacation downtime planning can affect the unit cost in a minor but consistent way. In general, the key is the maximization of the asset utilization, and the exploitation of the spring and fall months, that minimize the energy consumption of the paint booths. The production schedule organized in two shifts, 7 hours long, with a light shift of the vacation downtime shows low but consistent savings compared to having one shift, 10 hours long and higher production rate, achieving 3% lower unit cost. The rescheduling operation, if performed with common sense, could generate beneficial effects with minimal side costs.

5.2 Recommendations

This project has been carried out during the candidate's study at the University of Windsor. Time is a limited and precious resource, and the model has been developed respecting a strict timeline. Since the beginning, the winning choice has been to conceive the whole project as the integration of several modules that communicate and cooperate to generate the total result. This modularity can be used in the future to integrate and improve the model, adding new parts and refining the existent ones, without having to reshape the structure of the whole model [27]. Being able to benefit from more time and resources, some suggestions for future works are as follows.

- One of the improvements that would allow the model to predict the energy consumption of a paint shop in a more refined way is the simulation of the building HVAC. Unfortunately, it is a complex issue, because many parameters influence its result: internal buoyancy, physical dimensions of the plant, equipment volume occupancy, heat flows from and to the equipment in different conditions – as an example, the equipment in a machining plant emits considerable amounts of heat during production, because of the friction of the tool on the raw materials.
- Air Treatment Units energy consumption relies on an external module. A major step in the improvement of the paint shop energy model would be the generation of a leaner, less generic module, which would speed up the simulations.

- With further study, the pumping power in the pretreatment can be linked to the process requirements; the user would then be able to access and modify all the parameters of the pretreatment process.
- The air infiltration in the ovens is now considered as a constant value, which reflects the design requirements. It would be important to try and model the airflow through the air seals, linking its value to the air seal flow rate, aperture size, oven temperature, and incline and decline slopes. In this way, the infiltration air flow would be not be an input anymore, but another result of the model, and its value could be analyzed and optimization actions could be simulated to minimize it.
- An important improvement can be the refining of the calendar module. It has been conceived with a limitation: the production rate is assumed to be constant throughout the whole year and cannot be adjusted on a daily basis. A suggestion for an intermediate step would be the introduction of low-rate days, in which the production is slowed down to a certain value; this would be easy to integrate into the existing calendar module, and would give more freedom in the production schedule.
- In Michigan, the composition of the natural gas can vary considerably, leading to variations up to 30% of its heating value [28]. For the aims of this project, the average value of 35,000 kJ/m^3 has been considered, but further investigation could improve the accuracy of the result. Season, utilities company, and external temperature are among the parameters that affect the composition of the natural gas, and a detailed analysis was out of the scopes of this project.

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A. Appendix A

The Painting Process

In the following, a brief overview of the major steps of an automotive painting process will be illustrated, using where needed processes in the Sterling Heights Assembly Plant paint shop.

Pre-Treatment

The car body is usually delivered by the body shop to the paint shop, where it is transferred to a different carrier, since the paint accumulates on it. At the end of the process, before the delivery to the final assembly, the carrier is returned back and washed in a specific station.

The car body, as it arrives from the body shop, can be covered in dust and impurities that can be microscopic and non-detectable by naked eye. Ideally, to be painted, the surface has to be as clean and uniform as possible. Any kind of impurities can lead to a disastrous effect after the deposition of several layers of paint. Failures can be immediate or be detected by the customer just after the purchase. Keeping in mind that the paint is the most recognizable quality factor in a car, the importance of the pre-treatment is evident.

Initially, especially after summer shutdowns, difficult-to-clean car bodies are sprayed with a pre-clean mist that then recirculates to a tank and is then re-applied to subsequent car bodies, after which the car is pre-wiped by a small group of workers. The job is then rinsed off with automatic spray nozzles.

The subsequent stage is the deluge. It washes the car body exterior and the floor pan. Body shop debris (weld balls) of low buoyancy are removed from the car body. The job is washed with an alkaline cleaner solution, then it is sent down to a steep incline, in which the body interior is washed letting the water flow out of the front. At the bottom a series of spray nozzles washes the car while it is level and then it starts to rise into another incline, where the body interior is washed out letting the water flow out of the rear.

Then, the car body is chemically washed, being dipped into a tank filled with the same alkaline cleaner solution, and weld balls of neutral buoyancy are removed in this phase. The immersion can last up to several minutes, usually around two. The fluid used by both the deluge wash and dip desired temperature is around 52°C, so one or more heat exchangers are used to heat it.

It is very important, in the case of massive use of a process fluid, to have a system for its recirculation. This acquires a bigger importance when the process fluid is not simple water. Moreover, in case of contamination of the process fluid, it is fundamental to have a system that separates the contaminant from the liquid before recirculating it. The alkaline solution of the deluge processes carries weld balls and other residues that accumulated on the car body and that the pre-wash has not been able to wash away. They must be removed before recirculating the solution back for the subsequent jobs, and there are several ways to perform this operation:

- Gravity settling was the first method that has been used for solids removal from liquids, but it is very slow. Since the flow of process fluid is usually very high in a manufacturing process phase, a slow solids separation would mean having big settling basins to meet the process requirements.
- Filtration, using semi-permeable membranes.
- Use of hydrocyclones [29], conical vessels that operate by pressure drop, as shown in Figure A.1. The contaminated liquid enters the cone and starts to spin in a radial vortex pattern. Centrifugal forces act on the solid particles and make them discharge through the apex, while the liquid, because of the cone convergence, reverses its direction and discharge through the overflow stream. The particle size that is separated depends on the pressure drop through the hydrocyclone, which in turn depends on the inlet flow rate. Usually, particles can be separated if their size is larger than 10 μm.

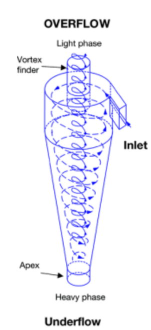


Figure A.1 - Hydrocyclone

After the deluge wash and dip, the car body is further spray rinsed and then dipped into city water, to rinse the body sections that cannot be sprayed. Before the phosphating dip, the car body is submerged into a conditioning bath, that creates a multitude of uniformly distributed starting points for phosphate coating crystal formation. The body is then rinsed with chemically treated alkaline "titanated" conditioner material in city water.

The car is then transferred to the phosphate dip tank; the purpose of which is to cover the car body with complex crystalline zinc phosphate conversion coating. It develops on the exterior, interior and all the enclosed sections to effectively protect the steel from corrosion. It is the first corrosion protection of the car body. Temperature, pH and chemical concentration must be well controlled and close to the ideal values to obtain a good quality coating.

The vehicle body is then rinsed with warmer than ambient city water, and then dipped in it. This is a very common pattern throughout the whole process, and it helps to reach all the surfaces that cannot be sprayed effectively. The car body is coated with a sealing agent to even and seal the rough crystalline phosphate coating. Formerly, the process involved the use of chromic acid, but now it is usually chrome-free and fluoro-zirconic acid may be used. That is because chrome is a polluting agent, and very difficult to treat as a waste product. After the sealing agent coating, the body is rinsed with warm water filtered by a reverse osmosis process. First it is sprayed then it is dipped in RO water.

Electro-Coat

The first stage of this sub-process is the electro-coat dip. Unlike the pre-treatment, there is no need to wash and rinse the surface before applying the coating. A gray epoxy water based paint, is deposited on the surface exploiting a voltage differential between the bath and the body. Reverse Osmosis processed water is used to totally wet the car body before entering the tank. A partially wet car body would show a wet-dry line after the coating process. The vehicle then enters the tank for a determined amount of time – it can be around 3 minutes. The paint inside the tank must be continuously circulated by big pumps to avoid coagulation. The car body is rinsed as it exits the dip, to get rid of excess “cream”.

The energy added by the circulating pumps results in a temperature rise of the bath. Since the conditions of the paint have to be extremely well-controlled to ensure a correct deposition – and being electricity deployed, the temperature is particularly important for the good quality of the outcome – one or more heat exchangers remove excess heat from the bath.

Several anodes are mounted along the sides of the tank to provide a strong DC charge to the paint. The body is grounded, and the voltage differential is exploited to deposit the paint on it. The anodes position is fundamental for the quality of the coating: enclosed sections and the floor can get a thinner and insufficient layer of paint deposited onto them compared to external panels. The anodes are usually fed with water called anolyte that carries excess acid from the painting process back to the anolyte tank.

The car body is further spray-rinsed and dipped, sometimes more than one time. The rinsing water is treated with an ultra-filtration method, which provides continuously clean rinse water and eliminates waste. It removes the paint from the dirty water, and it is also able to take the salts that originate from the evaporation away. The SHAP paint shop UF system can produce 100 gallons of UF rinse per minute.

De-Ionized water is then used to ultimately rinse the car body without leaving any salt residuals before the body enters the oven for curing. At this stage, the vehicle enters an e-coat oven, in which the deposited layer is cured. The temperature inside the chamber is usually around 180°C and the car body can stay inside for about half an hour. Its length is proportioned to the speed of the carrier, to reach the target time of curing. The SHAP paint shop has a dual pass e-coat oven, with the North and South passes that can work independently, and each of them is around 450 ft long. The ovens usually have an initial part in which the car body is increasing its temperature up to the desired value, then there is a stabilization zone in which its temperature stabilizes around the design value and then the car body enters the zone in which the actual curing occurs, called Convection-Hold. Strong air motion is usually needed inside the oven, to expose the painted surface to continuously renewed air and to reduce the solvent concentrations.

Several burners use fuel to heat up the air that circulates into the oven. They can be direct-fired or indirect-fired heaters, depending on their design. In a direct-fired burner the products of the combustion are mixed with the air in the output flow, while in an indirect-fired burner the products of the combustion are sent to a heat exchanger that heats up the air stream, leaving it free of combustion products. Usually in the first zones of the ovens, where the paint is still wet, the burners are indirect, to avoid to leaving impurities in the fresh coating.

The fresh air that circulates into the oven is usually a mixture of fresh and recirculated air. SHAP paint shop e-coat ovens use 20/80 fresh/recirculated air in the bring-up zone, while they use a 30/70 proportion in the hold section.

After the oven, the car body enters the condensate tunnel and a cooling tunnel in which colder air reduces the vehicle temperature prior to the next manned station.

Sealing

After the Electro Coat deposition and the curing of the e-coat, sealing and foams are applied on the car, to provide a barrier against water infiltration and to attenuate the noise in the cabin. This operation can be performed by men and/or automated stations. Usually, some robots work in series with 2-6 men.

The foam and sealant have to be cured into an oven right after their application, at a temperature that can be around 150°C. This baking cycle is typically shorter than the other ones, and the process variables are less strictly controlled. The SHAP paint shop sealer oven has four zones, all served by direct fired heaters. It has entry and exit air seals to keep the hot air inside the oven. The ratio between fresh and recirculated air is 15/85. After the oven, there is a cooling tunnel to lower the temperature of the car body before the next manned station.

Spray application

The subsequent processes are the application of the primer surfacer, basecoat and clearcoat. They are sprayed on the vehicle, and paint state and composition can vary according to the manufacturer choice, as already discussed in Section 2.1.1.

Powder Surfacer

After the application of the sealant, the vehicle is ready for the spray processes. The first step is the electrostatic deposition of a powder surfacer, that forms the second and last primer layer, and that guarantees further protection against corrosion and provides chip protection for the substrate.

The car body first enters the blow off zone, in which strong air flows blow residual particles off of the surface. It then goes into the main zone of the powder booth, in which vertical and overhead robots spray the powder surfacer towards the surface. The powder is pigmented, and it is possible to adapt its color to the final coating appearance: for dark colors, it is possible to spray gray powder, for lighter ones white powder is more suitable.

The SHAP paint shop powder booths have four couples of robots and one couple of manual guns that electrostatically spray the car body with gray or white powder. The pumps and the feeding systems are able to switch between the two colors without interruptions. The electrostatic deposition, as already discussed in the previous chapter, is fundamental to ensure the adherence of the paint on the surface and to avoid materials waste and uneven layering.

The pumps are one of the key elements that guarantee the operations of the powder application system; typically, the powder is fluidized and sent to small diameter delivery ducts, in which it behaves as a fluid and it becomes easier to direct to the applicators. Usually, a pump supplies more than one gun.

After the powder application, the car body is transferred to an oven for the curing of the coating. Typically, the baking temperature for powder is relatively high, and it is significant when modelling energy consumption. Depending on the manufacturer choice, the oven technology used can vary: it is possible to find radiation or convection ovens, and combinations of the two. Moreover, the air velocities in an oven for powder curing have to be low enough to not blow the coating off of the vehicle body, especially in the first part of the baking, but the air flow must be high enough to maintain the atmosphere within the oven below the LEL of the gases being released in the oven. Usually acceptable values are around $3 - 6 \quad ft/s$ [30].

SHAP paint shop has two 33-minute powder ovens that cure the output of a single powder booth. They are capable of 205°C and are heated by a combination of direct and indirect heater boxes. Each oven has seven zones, the first four being radiant, the fifth convection stabilization and the last two being convection hold zones. The incline and the decline have heated ceilings to prevent condensation. Both North and South ovens work with 25% fresh air in the radiant zones and 30% fresh air in the convection ones.

Powder Applicator

The applicator operation is governed by several compressed air flows. The main one is the dilution air, in which the powder is atomized and reaches the car body surface. A pushback or pilot flow generates the counter pressure that allows the powder to return back to the pump when the trigger on the gun is closed, and the shaping flow “wraps” the jet into a conical envelope and helps give directionality to the powder spray. The shaping air flow is usually generated by an external ring. The applicator operation can be schematized in different phases:

Spraying

The spray phase is initiated by the activation of the trigger. The powder flows towards the applicator, and the pinch valve, opened by cutting the pushback flow, opens the dilution air duct. In this way the powder is atomized into the dilution flow and it is sprayed out of the nozzle. Figure A.2 shows the operation of a spray applicator that uses compressed air.

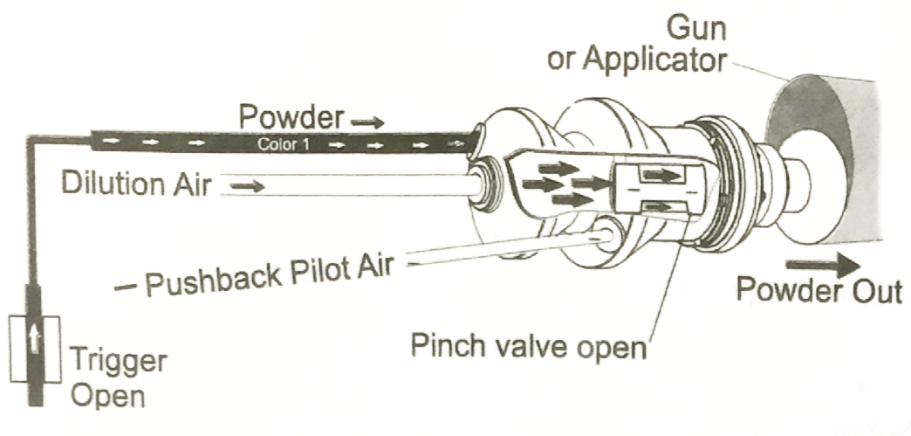


Figure A.2 - Spraying phase [31]

In Figure A.3 there is a 3D model of a round nozzle, with central electrode and air-cleaned front face. The low voltage of the power network is transformed into a high voltage input that is transferred to the central electrode on the front face, which is responsible for the powder charge. The powder deposits on the front face because of the electrostatic attraction, causing conductivity problems and poor spray quality. To solve this complication, a compressed air jet rinses the surface, keeping it clean and without powder deposits.

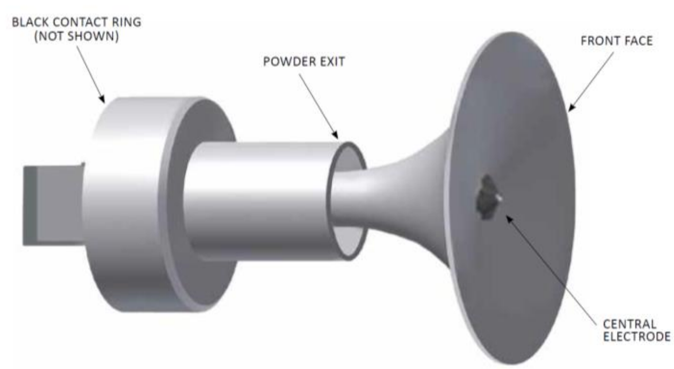


Figure A.3 – Nozzle [32]

Pushback

When the operator or the automatized process terminates the spraying operation, the pushback air duct is pressurized and closes the pinch valve. The powder trigger is maintained open to let the powder flow back to the pump, moved by the pushback pilot air pressure, as shown in Figure A.4. The dilution air flow is obstructed by the closure of the pinch valve.

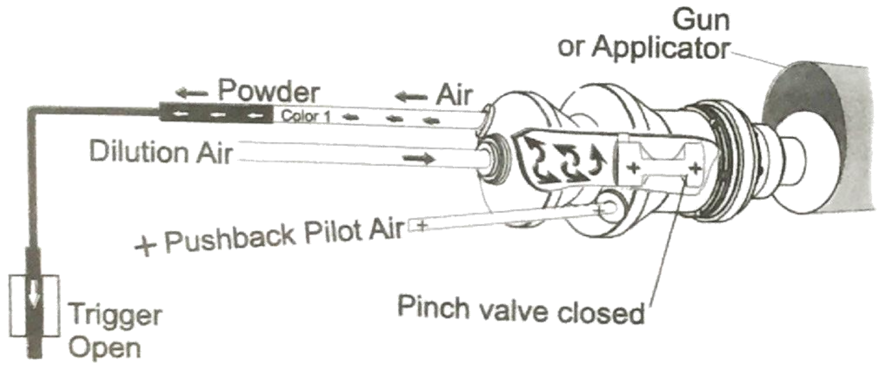


Figure A.4 - Pushback phase [31]

Wait

After all the powder has returned to the pump, the applicator changes its state autonomously into a wait condition. It is the only state in which the powder trigger is closed. The pushback air is again cut off and the pinch valve opens to let in the dilution air flow, in this case without carrying any powder. The applicator is ready for a new spraying cycle.

Topcoat

Nowadays, it is usual to apply the topcoat in two layers, basecoat and clearcoat, using a single, integrated booth and in a continuous process with a flash off – heated or at ambient temperature – between the two phases.

After the powder coating deposition and curing, the vehicle enters the Tack Off/Inspection booth, in which the vehicle body is inspected and prepared for the basecoat application. A blow off phase, similar to the one previous to the powder coating but more complex and usually multi-stage, removes dust particles and impurities that have deposited on the surface during the transfer time. The SHAP paint shop features a three-phase featherdust and blow off booth, in which the first two zones are fed with High-Efficiency Particulate Aerosol (HEPA) filtered air, and the third one uses the same air as the basecoat.

Following the blow off, the car body goes through the basecoat robotic application area, in which the first layer of the topcoat is applied, first on the interior and then on the exterior of the car. The length and complexity of this part of the booth depend on the type of paint that is applied on the car body and on the level of flexibility that is required; it's not uncommon to find multi-zone basecoat booths that allow for the quick basecoat color switch and for the application of mica and metallic paint. The transfer zones – blow off to basecoat, interior to exterior, basecoat to flash off – are usually pressurized, to avoid spread of impurities, and they can be called "air seals". The booths have floor grates with a wet scrubber underneath them, that uses water to remove paint particles from the air.

After the basecoat application, the vehicle goes into a flash off enclosure, in which air – which may be heated – is blown onto the surface to initiate the drying process of the paint layer. Usually the solids content of the coating is increased from approximately 50% prior the flash off to 80% after it. Humidity gained during the flash off process has to be removed by a dehumidification operation in the ATU.

Then, the vehicle goes through an air seal and a manual observation section, to get to the interior clearcoat robotic zone. The air that circulates during the whole clearcoat application is usually controlled and filtered: this last layer of coating, that gives the car the "glossy" finish – in the automotive lingo the clearcoat is called "shine" – is the most important element for aesthetic perception, and the air flow must be as pure as possible to obtain a virtually flawless result. An air seal section closes the clearcoat interior zone.

The car body enters then the clearcoat exterior robotic zone, in which several robots apply the last layer of coating onto its external surface, and it is transferred through a further air seal to the manual inspection area.

Typically, the air flow into the topcoat booths is made of 15% fresh air and 85% recirculated. As already discussed in the Paint chapter, nowadays a common choice is to employ a waterborne basecoat with solvent borne clearcoat. The exhaust of the clearcoat has then to be treated differently than that of the basecoat, and sent to an RTO or any other exhaust treatment system.

After the manual observation zone, the vehicle goes through an ambient flash and reaches the color oven, in which the topcoat is cured and after which the car appearance will be definitive.

The temperature required to cure the topcoat is around 150°C, much lower than the temperature inside the powder oven.

The SHAP paint shop has three parallel color booths that work simultaneously during full rate conditions. The first one is a multi-zone for mica application and special jobs, and it's longer than the other two, that are single-zone. Each booth has its own oven, all identical. The ovens use a combination of radiant and convection zones, and the baking cycle is around 33 minutes. The first two zones are radiant, the third is the convection stabilization and the final two zones are for the convection hold. A cooling tunnel at the end of the oven lowers the temperature of the car body before the next manned station.

Minor and Parallel processes

At this stage, the car is ready to be taken by the final assembly shop. The process that has been described in this chapter, however, is just the main stream, and the side/accessory processes have not been described. Ideally, to paint a car the phases that have been described up to this paragraph are enough for the completion of the process. But for every inspection zone along the whole process there is a side stream in which defective jobs are repaired, with dedicated booths, manpower, and equipment. This affects the energy consumption and the floor space occupation by a non-negligible amount.

B. Appendix B

The SHAP paint shop energy model, as discussed in the previous sections, accounts several variables, each of them being more or less important for the final result. It is important to highlight that part of the value of this project was given by the "virtual environment" described by the left hand side of the diagram in Figure 3.3, hence some of the variables that are reported below had been inserted in the model with the sole aim of completing the inventory operation. The paint shop data that can be input into the model is summarized in the following.

- Weather
  - hourly temperature, averaged for every month
  - hourly humidity, averaged for every month
- pumps:
  - power readings from meters and/or energy studies
  - motor HP
  - information about flow rate and head pressure
  - tag and location
  - information on use during production
- fans:
  - power readings from meters and/or energy studies
  - motor HP
  - information about airflow and pressure drop
  - tag and location
  - information on use during production
- tanks:
  - external and internal dimensions
  - bath temperature
  - information about recirculation pumps actual power
  - tag and location
  - information about walls temperature
    - a rough estimate is acceptable
  - carrier/car body mass and material properties
- heat exchangers:
  - rating
  - information on flow rates of hot and cold fluids
  - in and out temperature of hot and cold fluids
- phosphating and e-coat
  - plant temperature

    - cold water temperature out of distribution network
- ovens
    - set point temperature
    - zone temperatures
    - air flow information
        - fresh air and recirculation air
    - external and internal dimensions
    - walls material properties
    - insulant layer properties
    - inside air velocity at walls
        - a rough estimate is acceptable
    - outside walls temperature
        - a rough estimate is acceptable
    - ovens' carrier mass and material properties
    - infiltration airflow
    - maximum allowed production rate for each oven
- booths and decks
    - set point temperature and humidity
    - airflow requirements for every zone
    - recirculation requirements for every zone
    - external and internal dimensions
    - lighting requirements for every zone
    - maximum allowed production rate

To obtain the energy consumption of a paint shop, however, not all of these variables are necessary. To be able to use the paint shop energy model on another plant, only a few steps are required:

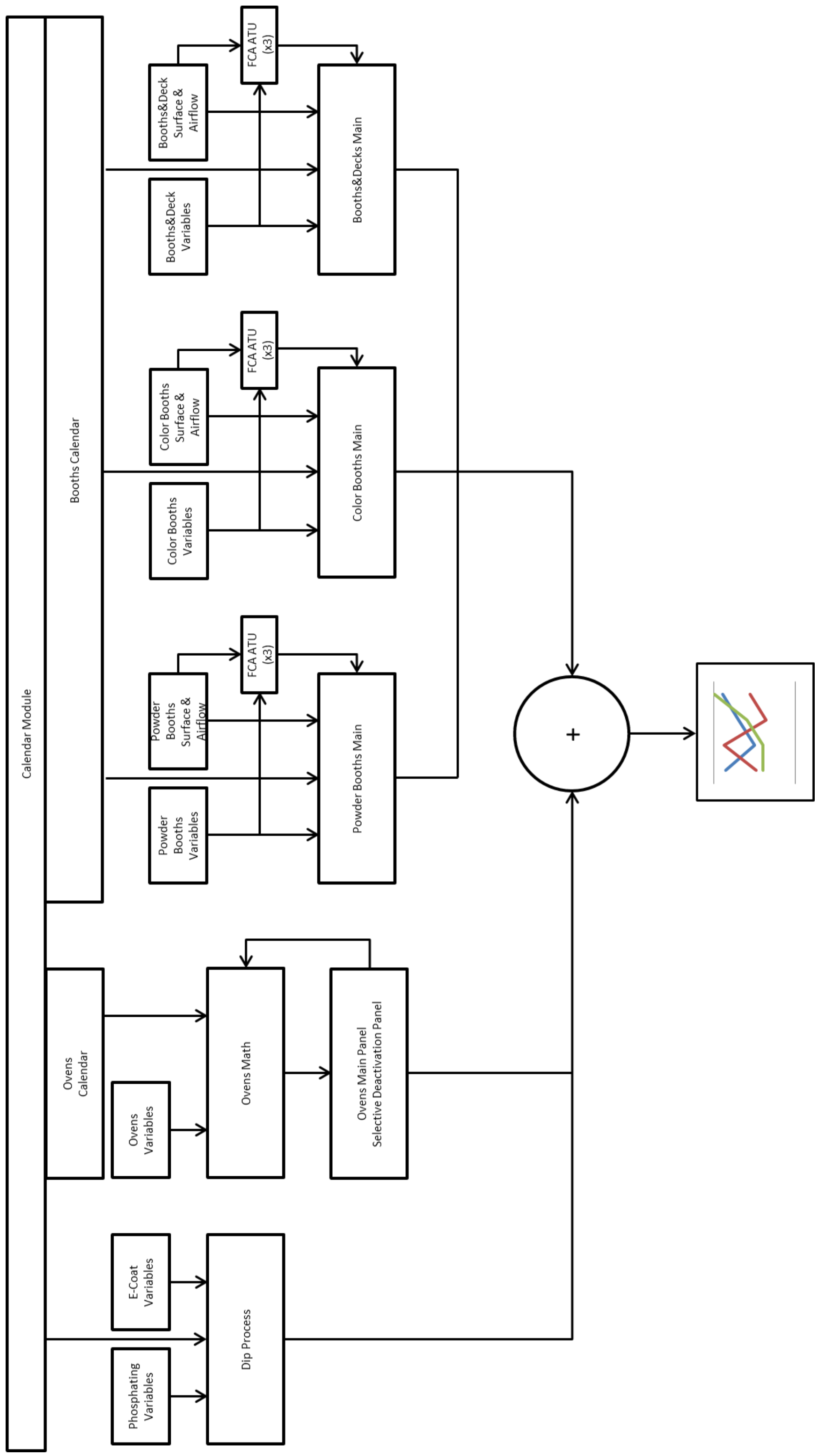
- information regarding the weather of the location in which the plant has been built must be retrieved, preferably using the EnergyPlus® website [20].
- Tanks dimensions and capacities for **pretreatment** and **e-coat** have to be input in the model, and can be found in the specific paint shop documentation (usually provided by the paint shop manufacturer and residing at the plant), along with bath temperature requirements, and information about the car body and carrier mass, tanks' throughput, and materials of the tanks' walls. Pumps actual energy consumption data need to be collected using the STEP1 worksheet, and usually the paint shop documentation contains all the information for it. It is suggested then to walk along the line to check the tags of the pumps for correspondence. Information about the plant temperature during winter and summer seasons is required for a more accurate computation of the heat

transfer through the tanks' walls. Data on operating values can also be obtained from the FIS.

- **Ovens:** set point temperatures, dimensions, walls' material and thickness, required airflow and recirculation, infiltration airflow, carrier mass and material, and admitted throughput are required, and are usually easily retrieved from the paint shop documentation. Outside wall temperatures and inside wall air velocities can be estimated without considerably affecting the accuracy of the model.
- **Booths:** set point temperature and humidity, dimensions, airflow and recirculation requirements for each zone, lighting, and admitted production rate can be usually found in the documentation relative to the paint shop.

Using these pieces of information in the paint shop energy model allows the computation of the energy consumption of any paint shops that use the same coating process as described in Appendix A. Considering the modularity of the model, to adapt this tool to a plant with a different coating process a minimal amount of modifications should be needed.

Block diagram of the paint shop energy model



Vita Auctoris

NAME:	Marco Gerini Romagnoli
PLACE OF BIRTH:	Torino, Italy
DATE OF BIRTH:	1992
EDUCATION:	Politecnico di Torino, B.Sc. in Automotive Engineering, Torino, Italy, 2014
	Politecnico di Torino, Master in Automotive Engineering, Torino, Italy, 2016
	University of Windsor, International M.A.Sc. in Mechanical Engineering, Windsor, Canada, 2016