ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

INGENIERO INDUSTRIAL

ENERGY AUDIT OF A PAINT BOOTH

Autor: Clara Jiménez Serrano
Director: Caglar Canbay

Madrid
Junio 2018

Clara
Jiménez
Serrano

ENERGY AUDIT OF A PAINT BOOTH

AUTHORIZATION FOR DIGITALIZATION, STORAGE AND DISSEMINATION IN THE NETWORK OF END-OF-DEGREE PROJECTS, MASTER PROJECTS, DISSERTATIONS OR BACHILLERATO REPORTS

1. Declaration of authorship and accreditation thereof.

The author Mr. /Ms. CLARA JIMÉNEZ SERRANO

HEREBY DECLARES that he/she owns the intellectual property rights regarding the piece of work: ENERGY AUDIT OF A PAINT BOOTH
that this is an original piece of work, and that he/she holds the status of author, in the sense granted by the Intellectual Property Law.

2. Subject matter and purpose of this assignment.

With the aim of disseminating the aforementioned piece of work as widely as possible using the University's Institutional Repository the author hereby **GRANTS** Comillas Pontifical University, on a royalty-free and non-exclusive basis, for the maximum legal term and with universal scope, the digitization, archiving, reproduction, distribution and public communication rights, including the right to make it electronically available, as described in the Intellectual Property Law. Transformation rights are assigned solely for the purposes described in a) of the following section.

3. Transfer and access terms

Without prejudice to the ownership of the work, which remains with its author, the transfer of rights covered by this license enables:

a) Transform it in order to adapt it to any technology suitable for sharing it online, as well as including metadata to register the piece of work and include "watermarks" or any other security or protection system.
b) Reproduce it in any digital medium in order to be included on an electronic database, including the right to reproduce and store the work on servers for the purposes of guaranteeing its security, maintaining it and preserving its format.
c) Communicate it, by default, by means of an institutional open archive, which has open and cost-free online access.
d) Any other way of access (restricted, embargoed, closed) shall be explicitly requested and requires that good cause be demonstrated.
e) Assign these pieces of work a Creative Commons license by default.
f) Assign these pieces of work a HANDLE (*persistent* URL). by default.

4. Copyright.

The author, as the owner of a piece of work, has the right to:

a) Have his/her name clearly identified by the University as the author
b) Communicate and publish the work in the version assigned and in other subsequent versions using any medium.
c) Request that the work be withdrawn from the repository for just cause.
d) Receive reliable communication of any claims third parties may make in relation to the work and, in particular, any claims relating to its intellectual property rights.

5. Duties of the author.

The author agrees to:

a) Guarantee that the commitment undertaken by means of this official document does not infringe any third party rights, regardless of whether they relate to industrial or intellectual property or any other type.

b) Guarantee that the content of the work does not infringe any third party honor, privacy or image rights.
c) Take responsibility for all claims and liability, including compensation for any damages, which may be brought against the University by third parties who believe that their rights and interests have been infringed by the assignment.
d) Take responsibility in the event that the institutions are found guilty of a rights infringement regarding the work subject to assignment.

6. Institutional Repository purposes and functioning.

The work shall be made available to the users so that they may use it in a fair and respectful way with regards to the copyright, according to the allowances given in the relevant legislation, and for study or research purposes, or any other legal use. With this aim in mind, the University undertakes the following duties and reserves the following powers:

a) The University shall inform the archive users of the permitted uses; however, it shall not guarantee or take any responsibility for any other subsequent ways the work may be used by users, which are non-compliant with the legislation in force. Any subsequent use, beyond private copying, shall require the source to be cited and authorship to be recognized, as well as the guarantee not to use it to gain commercial profit or carry out any derivative works.
b) The University shall not review the content of the works, which shall at all times fall under the exclusive responsibility of the author and it shall not be obligated to take part in lawsuits on behalf of the author in the event of any infringement of intellectual property rights deriving from storing and archiving the works. The author hereby waives any claim against the University due to any way the users may use the works that is not in keeping with the legislation in force.
c) The University shall adopt the necessary measures to safeguard the work in the future.
d) The University reserves the right to withdraw the work, after notifying the author, in sufficiently justified cases, or in the event of third party claims.

Madrid, on 29....... of ....June................, ..2018..

HEREBY ACCEPTS

Signed..CLARA JIMÉNEZ SERRANO.....................

Reasons for requesting the restricted, closed or embargoed access to the work in the Institution's Repository

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

ENERGY MAPPING OF A PAINT BOOTH

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el curso académico ....2017/18.......... es de mi autoría, original e inédito y no ha sido presentado con anterioridad a otros efectos. El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido tomada de otros documentos está debidamente referenciada.

Fdo.: Clara Jiménez Serrano Fecha: 29/ 6/ 2018

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Caglar Canbay Fecha: 29/ 6/ 2018

UNIVERSIDAD PONTIFICIA
ICAI ICADE
COMILLAS
MADRID

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

INGENIERO INDUSTRIAL

ENERGY AUDIT OF A PAINT BOOTH

Autor: Clara Jiménez Serrano
Director: Caglar Canbay

Madrid
Junio 2018

Clara
Jiménez
Serrano

ENERGY AUDIT OF A PAINT BOOTH

AUDITORÍA ENERGÉTICA DE UNA CABINA DE PINTURA

Autor: Jiménez Serrano, Clara.

Director: Canbay, Caglar

Entidad Colaboradora: Toyota Motor Europe

RESUMEN DEL PROYECTO

La energía es clave tanto para el crecimiento económico como para el bienestar de los ciudadanos. Sin embargo, el aumento previsto de la demanda energética en los próximos años y el agotamiento de los recursos han hecho de la energía un tema prioritario tanto para los gobiernos, como para las empresas.

En los últimos años las empresas relacionadas con la producción se han hecho más responsables en cuanto a sus productos y procesos. De hecho, han estado introduciendo medidas para reducir su impacto medioambiental y conseguir un uso de la energía más eficiente.

Entre todas ellas, destaca Toyota, empresa líder en la fabricación de vehículos, muy conocida por su preocupación por el medioambiente y por invertir en tecnología verde. Se ha propuesto como objetivo primordial conseguir para 2050 cero emisiones de CO_2 en cualquier ámbito de su negocio.

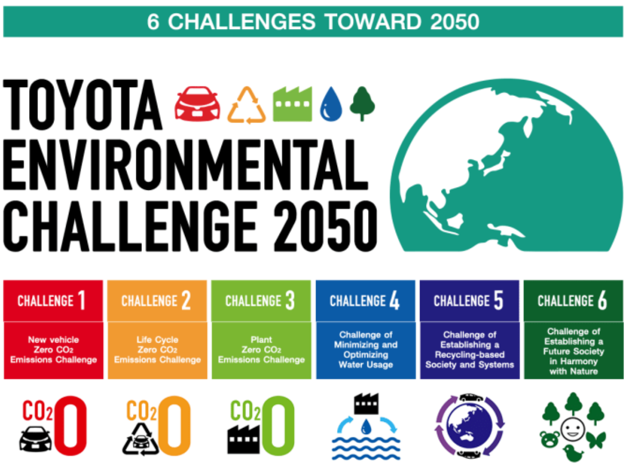


Imagen 1. Desafío medioambiental de Toyota para 2050

Los automóviles no solo producen CO_2 cuando se conducen, sino también cuando se fabrican. Por ello, el desafío medioambiental de Toyota también engloba el conseguir cero emisiones de CO_2 en sus plantas de fabricación.

Cuando se trata de eliminar cualquier consumo extra, las auditorías energéticas son el método más usado por las compañías. Se trata de un método basado en la investigación, estudio y análisis de los flujos de energía de los diferentes procesos con el fin de introducir medidas para su ahorro sin que estos o la calidad del producto final se vean comprometidos.

Uno de los procesos más críticos en cuanto a calidad es el de la pintura. La pintura protege contra la corrosión y la oxidación, además de dar la apariencia final al vehículo. Este proceso consume cerca de la mitad de la energía necesaria en la fabricación de vehículos[FENG15]. Por ello, el objetivo de esta tesis será realizar una auditoría energética en la cabina de imprimación del proceso de pintura de la fábrica francesa de Toyota para entender su consumo de energía, así como generar una posible lista de medidas para un uso más eficiente.

Una cabina de pintura es un cuarto cerrado que evita que los gases y partículas que resultan del proceso salgan al exterior. Normalmente, se utiliza para aplicar las dos últimas capas del proceso de pintura. La Imagen 2 muestra sus diferentes pasos [ARTI13].

Imagen 2. Método de pintura.

En la auditoría energética se seguirá un proceso sistemático.

En primer lugar, se realizará un mapeo energético para entender cómo la energía fluye dentro del proceso.

Una vez detectados los principales consumidores de energía, se elaborará un plan para conseguir los datos necesarios de cada uno. Algunos, se obtendrán a través del programa OSISoft, que registra información de la fábrica proporcionada por diferentes sensores, y para extraer otros será necesario ir a medir a la propia fábrica.

Teniendo toda la información, se realizará un diagrama de flujo para ayudar a visualizar el consumo y las pérdidas del proceso. La Imagen 3 muestra cómo la energía se distribuye en la cabina.

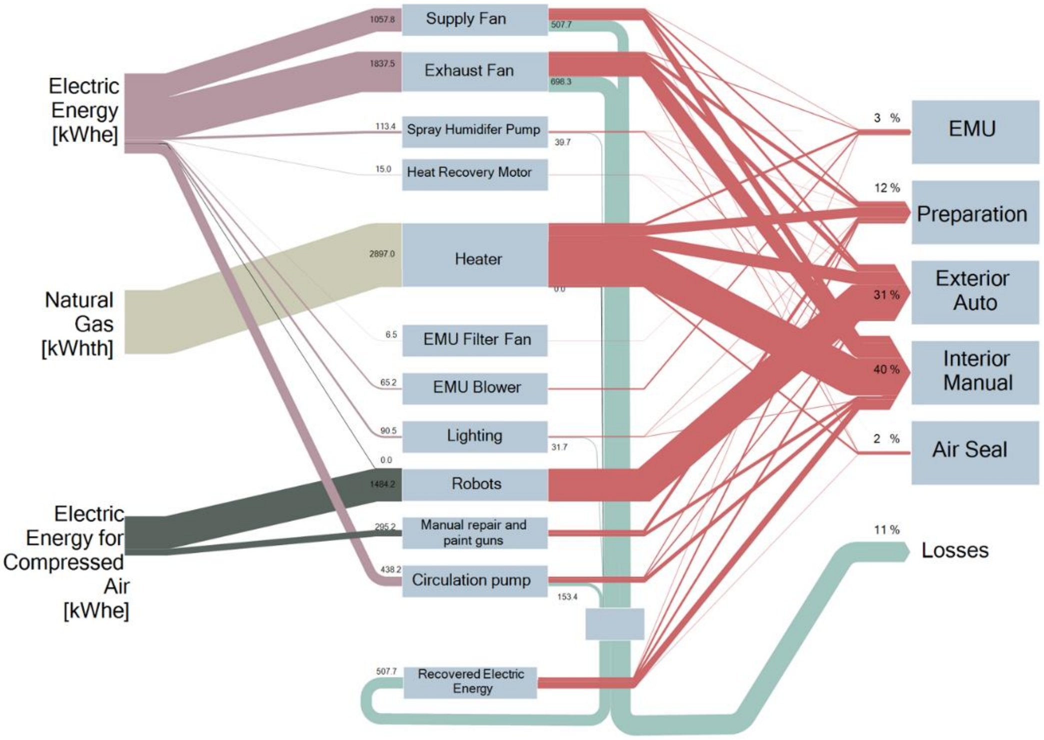


Imagen 3. Diagrama de Sankey del proceso de imprimación

En segundo lugar, la auditoría se centrará en el estudio de arranque y parada de los equipos de la cabina de pintura. Con ello, se tratará de mejorar su operación para llegar a un mejor procedimiento y ahorrar energía durante el tiempo de no producción.

En tercer lugar, tras entender cómo se usa la energía en la cabina de imprimación, se generará un listado de mejoras. Estas se clasificarán en:

- Acciones para la conservación de energía: aquellas relacionadas con la forma de operar los equipos, como son el procedimiento de arranque y parada o de mantenimiento. En general, no se requiere casi inversión.

- Acciones para la mejora de eficiencia energética: aquellas en las que se requiere el cambio físico de algún equipo. El objetivo es conseguir la tecnología más eficiente. En general, se requiere una gran inversión inicial.

Finalmente, su impacto energético y medioambiental se evaluará y se establecerá el orden óptimo de implantación.

Entrando en la parte más técnica, tras el análisis se estableció que una gran cantidad de energía podría ser ahorrada cambiando tan solo la forma de operación del equipo. Asimismo, un mayor ahorro se podría conseguir con el cambio a una tecnología más eficiente.

Un total de 8908 MWh por año son consumidos en la cabina de imprimación. Si se implementasen las medidas de conservación de energía se obtendría un ahorro del 17.9 % y se ahorraría un 0.5 % adicional sobre el valor inicial de implementarse las medidas de mejora de eficiencia. Por último, las emisiones de CO_2 se podrían llegar a reducir hasta 190 toneladas por año de las 831 consumidas al año.

Aunque los resultados no pueden extrapolarse a otras plantas porque cada una usa una tecnología diferente, la metodología seguida sí. Además, si el mismo estudio se realizase en otras plantas, se podría establecer la mejor tecnología para el proceso.

BIBLIOGRAFÍA

[FENG15] Feng, L., Laine Mears, "Analysis of HVAC Energy in Automotive Paint Shop", ASME 2015 International Manufacturing Science and Engineering Conference, vol. 2, Charlotte, 2015.

[ARTI13] Artid. Trakultongchai, Srisawat. Supsomboon, and Kamol. Limtanyakul, "Process Simulation and Improvement of Automotive Paint Shop", International Journal of Mining, Metallurgy & Mechanical Engineering, vol 1, pp. 2320-4060, 2013.

ENERGY AUDIT OF A PAINT BOOTH

Author: Jiménez Serrano, Clara.

Director: Canbay, Caglar

Collaborating Entity: Toyota Motor Europe

PROJECT SUMMARY

Energy is a key for economic growth and prosperity. However, the expected demand growth in the next years and the limited resources have made energy related issues a top priority for both the government and organizations.

Organisations have become more responsible regarding their products and processes. That is why not only have they introduced measures to use the energy more efficiently but also to reduce their environmental impact. In particular those related with manufacturing activities.

In this context, Toyota highlights. The company is well known for caring about the environment and for investing in environmental technologies. Moreover, it has challenged itself to achieve by 2050 zero CO_2 emissions on every dimension of its business.

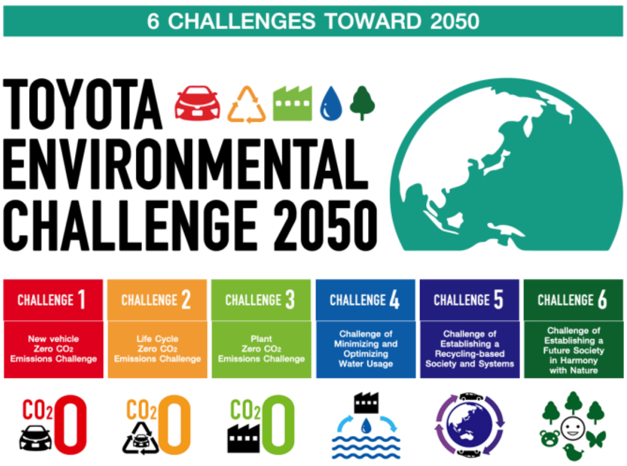


Figure 1. Toyota Environnemental Challenge 2050
Source : Internet, http://www.toyota-global.com/sustainability/environment/challenge2050/

As an automotive organization Toyota's vehicle generate CO_2 emissions both while driving them and when producing them. That is why as part of its Environmental Challenge Toyota aims to reach zero CO_2 emissions not only in its cars but also in its manufacturing plants.

When trying to reduce any extra energy consumption, energy audit is the most popular method among companies. This technique is based on the investigation, study and analysis of energy flows of different processes in order to introduce energy saving measures without compromising the manufacturing process and its quality.

One of the most important processes to ensure a good quality of the vehicles is the painting process. Painting gives the vehicle both a protection layer to fight corrosion and oxidation and its appearance. In addition, it happens to use close to half of the energy of the automotive assembly process [FENG15]. Therefore, this thesis will aim to understand the energy consumption across the primer booth of the paint shop in the Toyota's manufacturing plant in France and it will generate a list of possible actions to manage energy more efficiently.

A painting booth is an enclosed room that protects the working environment from paint's particle matter and gasses. Generally, it is used to apply the two final layers of the painting process. Figure 2 shows the total steps followed in car manufacturing [ARTI13].

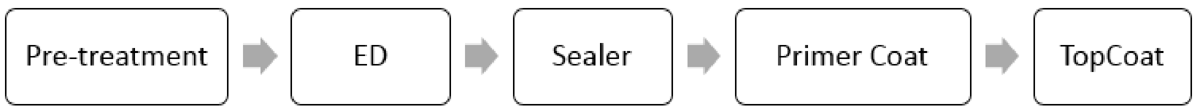


Figure 2. Coating process

When performing the energy audit on the primer booth a systematic methodology will be followed.

Firstly, an energy mapping will be carried out to understand the energy usage and breakdown of the paint booth.

Having defined the scope of the energy study, energy consumers will be listed. Then, the potential measurements points will be established and a plan to obtain the data from the equipment will be elaborated. Afterwards, the study will require to go on-site to measure the consumption of the paint booth. Once all the data is gathered its assessment will take place. This stage of the audit will finish with an energy flow diagram that will help to visualise how the energy goes through the paint booth and where the main losses are concentrate. Figure 3, apart from showing how energy is distributed across the primer booth, it also shows its main energy consumers.

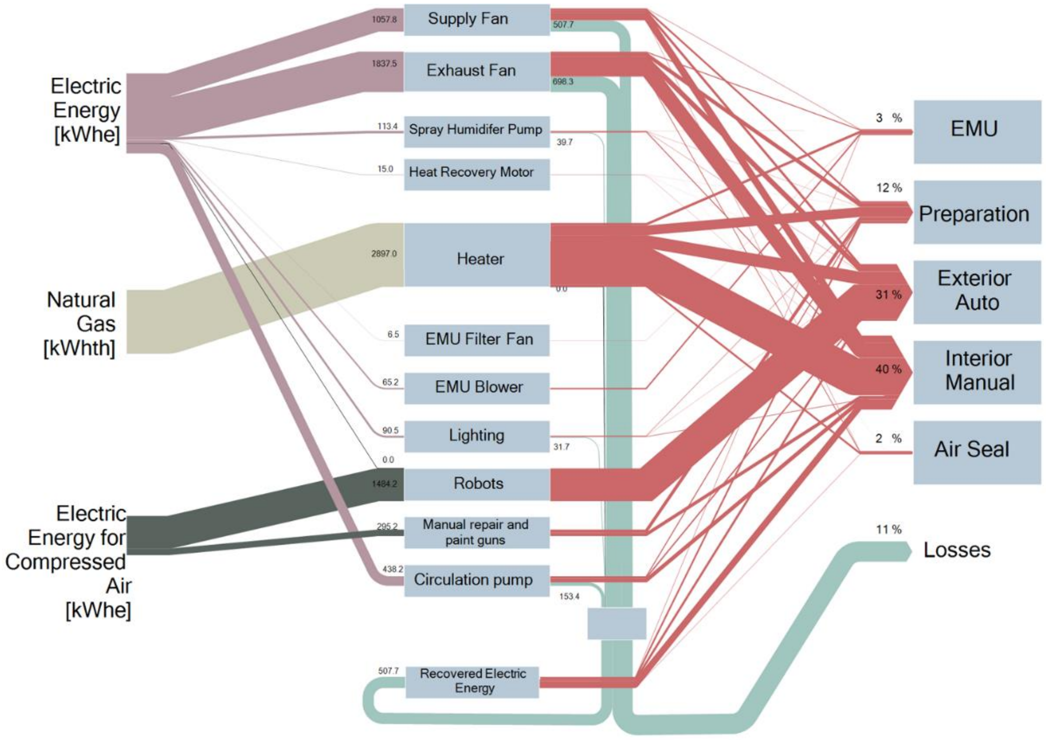


Figure 3. Sankey diagram of Primer Booth

Secondly, the audit will focus on studying the start and stop process of the paint booth. This analysis will try to improve the operational behaviour of the equipment involved in the process and get a better start stop procedure, so energy is saved during non-production.

Thirdly, after understanding how the energy is utilized in the paint booth during the painting process a list of potential improvements will be proposed. Two different energy reduction actions will be studied:

- Energy Conservation actions: Items related with behavioural matters. They aim to get the best operation and maintenance. Generally, they are no cost or low cost to implement.

- Energy Efficiency Improvement actions: Items that require physical modifications of the equipment. They aim to get the best efficient technology. Moreover, they normally require big investment.

Finally, their environmental and energetic impact will be analysed so it could be established the optimal order to implement them.

Focussing on the technical part, analysis showed that a large amount of energy could be saved just by changing the operational behaviour of the equipment. Further savings could also be achieved by changing the current technology into a more efficient one.

A total of 8908 MWh per year is what the primer booth is currently consuming. If implementing energy conservation measurements, a 17.9 % of the energy could be saved. Moreover, whether Energy Efficiency improvements were introduced, an additional 0.5% would be saved over the original energy consumption. In addition, CO2 emissions could be reduced up to 190 tons of CO_2 per year.

Although results could not be extrapolated to other plants as each uses a different technology, the methodology followed could. Moreover, this study could be performed in other plants so the best technology available could be grasped.

BIBLIOGRAFY

[FENG15] Feng, L., Laine Mears, "Analysis of HVAC Energy in Automotive Paint Shop", ASME 2015 International Manufacturing Science and Engineering Conference, vol. 2, Charlotte, 2015.

[ARTI13] Artid. Trakultongchai, Srisawat. Supsomboon, and Kamol. Limtanyakul, "Process Simulation and Improvement of Automotive Paint Shop", International Journal of Mining, Metallurgy & Mechanical Engineering, vol 1, pp. 2320-4060, 2013.

Table of Contents

Table of Figures

Table of Tables

Chapter 1

Introduction

Energy is a key for economic growth and prosperity. It plays a main role in the development of any country and it is fundamental for the well-being of its citizens. Therefore, due to the great impact that it has on society it is topic very present not only in the scientific, but also in the political, social and economic field [FYSI12].

Currently, the energy sector is facing technological, environmental and regulatory changes driven by factors such as demand, natural resources and environment.

Historically, economic growth has gone in parallel with an increase in the energy demand. Inevitably, fast population growth and rapid growing economies result in a higher energy utilization. In the future years this increase is expected to be around 28% [EIA_17]. Different sources vary on the exact percentage. However, all of them agree that in the following years energy consumption will increase.

On the contrary, resources are characterised by their constant depletion. Mayor concerns have been raised over the years about the continuous increase of energy demand and the decrease of resources. Therefore, different initiatives have been carried out to reduce energy consumption.

In addition, the current problem with emissions and climate change have made the search for new solutions even more urgent.

All these facts, the increase of demand, the decrease of resources and the pollution, challenge not only individuals and governments, but also private companies. Now, they are demanded to have stricter policies regarding energy consumption and environment. Nevertheless, organisations have adapted and have become more responsible regarding their products and processes. Currently, they invest more in analysing their energy utilization and in changing their performances, so they have a more efficient energy consumption.

This continuous search for energy improvement in technologies and processes is the result of the proactive green behaviour that companies have been developing. Also, possibly lead by the increase of energy prices or by the brand image as a result of the recent environmental awareness.

When trying to reduce the extra energy consumption organizations carry out regular energy audits. This technique is based on the investigation, study and analysis of energy flows of different processes to manage energy more efficiently. As energy audits work on technologies and operations used daily, they could result on potential energy savings.

Among the advantages of conducting energy audits, the following three highlights:

- Reduction of contamination emissions.
- Reduction of costs: generally energy efficient technologies have a lower maintenance cost.
- Better understanding of energy consumption.

From an energy audit several optimization measures could be extracted that could lead to energy reduction. However, not all of them can be implemented at the same time. Therefore, the energy audit process has to be followed by a prioritization of these measures.

Chapter 2

TOYOTA

When studying energy utilization, the industry sector is the one with the largest energy consumption. Moreover, it is expected to keep increasing. However, not at the same speed as the others [EIA_17]. Figure 4 presents the expected energy consumption for the industrial sector in the next years.

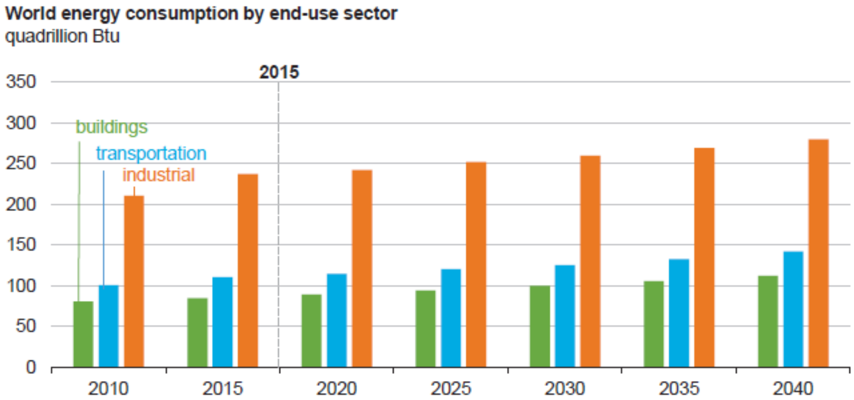


Figure 4. Energy utilization by sectors
Source: "International Energy Outlook 2017", Energy Information Administration (EIA),2017

Being the industrial sector the one with the highest energy consumption means that among the different industries there is a vast potential of energy saving measures that could be applied [OUME16]. Due to the infinite possibilities this thesis will only focus on the car manufacturing industry. Figure 5 shows the car production history in Europe.

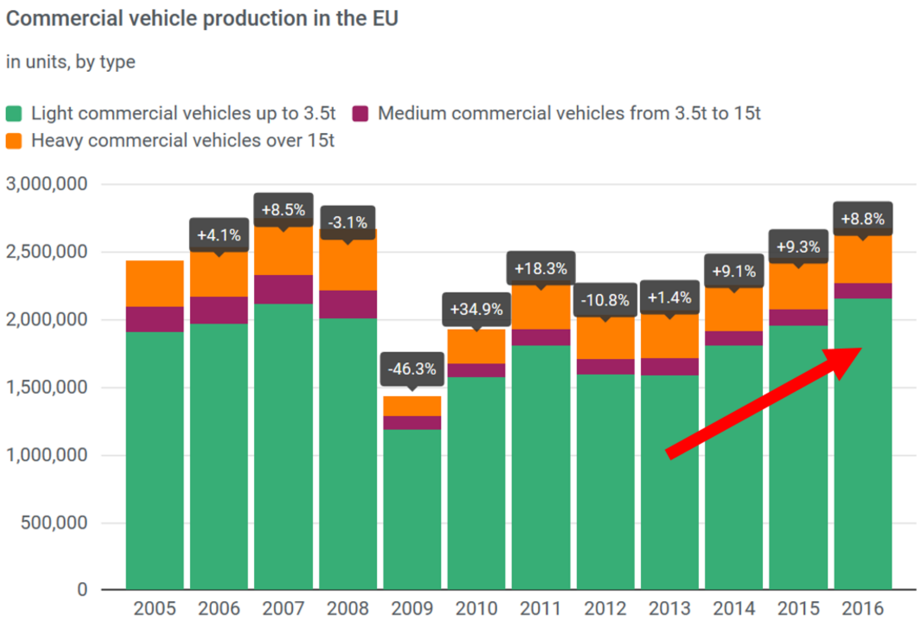


Figure 5. Car manufacturing history
Source: Internet, http://www.acea.be/statistics/article/world-commercial-vehicle-production

This industry is expected to keep growing. Therefore, its impact on the environment will also increase as for its daily production renewable and non- renewable resources are used [DUFL12]. Nevertheless, over the years vehicle production companies have been introducing measures not only to use the energy more efficiently but also to reduce their environmental impact [SEOW11].

Among these Toyota highlights. The organization is well known for caring about the environment and for investing in environmental technologies. Moreover, it has challenged itself to achieve by 2050 zero CO_2 emissions on every dimension of its business.

2.1 Background

Toyota was founded in 1937 by Kiichiro Toyoda and since that moment the company has grown into becoming one the world’s largest manufacturers selling cars in more than 170 countries and regions all over the world [TOYO__].

Toyota’s main headquarters are based in Japan where it also has more than 10 different manufacturing plants. Moreover, outside Japan, Toyota has 53 manufacturing companies in

28 countries and regions. In particular, in Europe, Toyota owes 9 plants in 7 different countries:

1. Toyota Caetano Portugal S.A. in Ovar
2. Toyota Motor Manufacturing France SAS in Onnaing
3. Toyota Motor Manufacturing United Kingdom Ltd. in Deeside
4. Toyota Motor Manufacturing United Kingdom Ltd. in Burnaston
5. Toyota Peugeot Citroën Automobile Czech in Kolin
6. Toyota Motor Manufacturing Poland Sp.zo.o in Walbrzych.
7. Toyota Motor Manufacturing Poland Sp.zo.o in Jelcz-Laskowice
8. Toyota Motor in Saint-Petersburg
9. Toyota Motor Manufacturing Turkey INC. in Arifiye/Sakarya

All these plants are supported by Toyota Motor Europe (TME), the European headquarters, located in Brussels, Belgium. Figure 6 shows the different manufacturing plants managed by the Europe division. Name numbering corresponds with the list above.

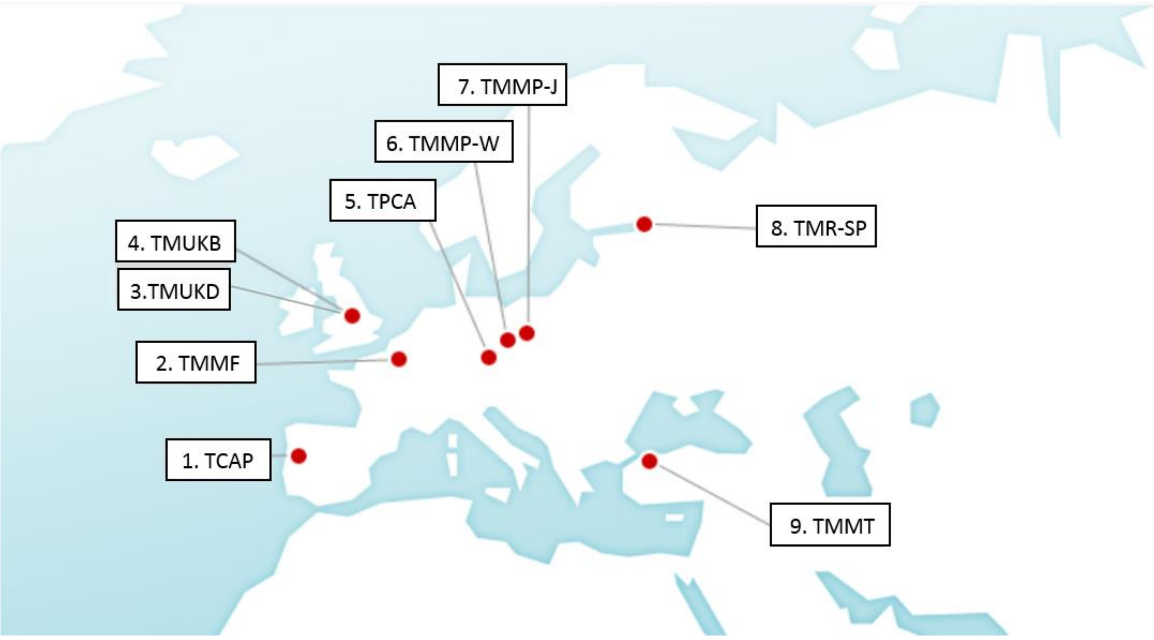


Figure 6.Toyota's manufacturing facilities in Europe
Source : Internet, https://www.toyota-europe.com/world-of-toyota/feel/operations/made-in-europe/manufacturing

Six out of the nine manufacturing sites produce vehicles. The other three focus on transmissions and engines, see Table 1.

Plant	Production
TMUKD	Engine
TMUKB	Vehicle
TMMT	Vehicle
TPCA	Vehicle
TMMP	Engine
TMIP	Engine
TMMF	Vehicle
TMMT	Vehicle
TCAP	Vehicle

Table 1. Toyota's production

However, Toyota not only stands out for its international scope but also for its philosophy. The Toyota Way, as it is called, it is based on continuous improvement and respect for people. These two principles complement the company's main desire to contribute to society by manufacturing vehicles [TOYO__]. Furthermore, Toyota has also been very committed to the environment, for instance, it was the first vehicle production company to mass-produce the hybrid vehicle. In this context, it has challenged itself to reduce CO_2 emissions by 2050.

2.2 Environmental challenge [TOYO15].

As an automotive organization, Toyota's vehicles generate CO_2 emissions both while driving and producing them. That is why as part of its Environmental Challenge Toyota aims to reach zero CO_2 emissions not only in its cars but also in every step of its production cycle. Being set for 2050, it is divided in six challenges and it covers every aspect of Toyota's business:

1. <u>New Vehicle Zero CO_2 Emissions</u>: Toyota is planning to reduce car's CO_2 by 90% in comparison with 2010 by developing the next generation car with low or zero CO_2 emissions.

2. Life Cycle Zero CO_2 Emissions: Toyota will work in reducing the CO_2 not only when manufacturing but also when extracting and recycling materials or disposing vehicles.

3. Plant Zero CO_2 Emissions: reducing emissions in vehicles is not linked to reducing emissions in their production. Therefore, plant emissions are expected to be reduced by improving manufacturing technology and using different types of energy.

4. Minimising and Optimising Water Usage: being aware that probably in the near future population will suffer water shortages, Toyota aims to minimize its water utilization. Among the measures implemented are recycling water, collecting rainwater or reducing consumption.

5. Establishing a Recycling-based Society and Systems: due to the large quantity of waste currently generated it will be unfeasible to dispose all in the future. That is why Toyota seeks for a usage of eco-friendly materials, for a longer usage of parts and for a development of a recycling technology.

6. Establishing a Future Society in Harmony with Nature: this challenge aims to ensure that humans and nature can be able to coexists by contributing to environmental education or assisting environmental activities.

Figure 7 summers up the Toyota Environmental Challenge for 2050

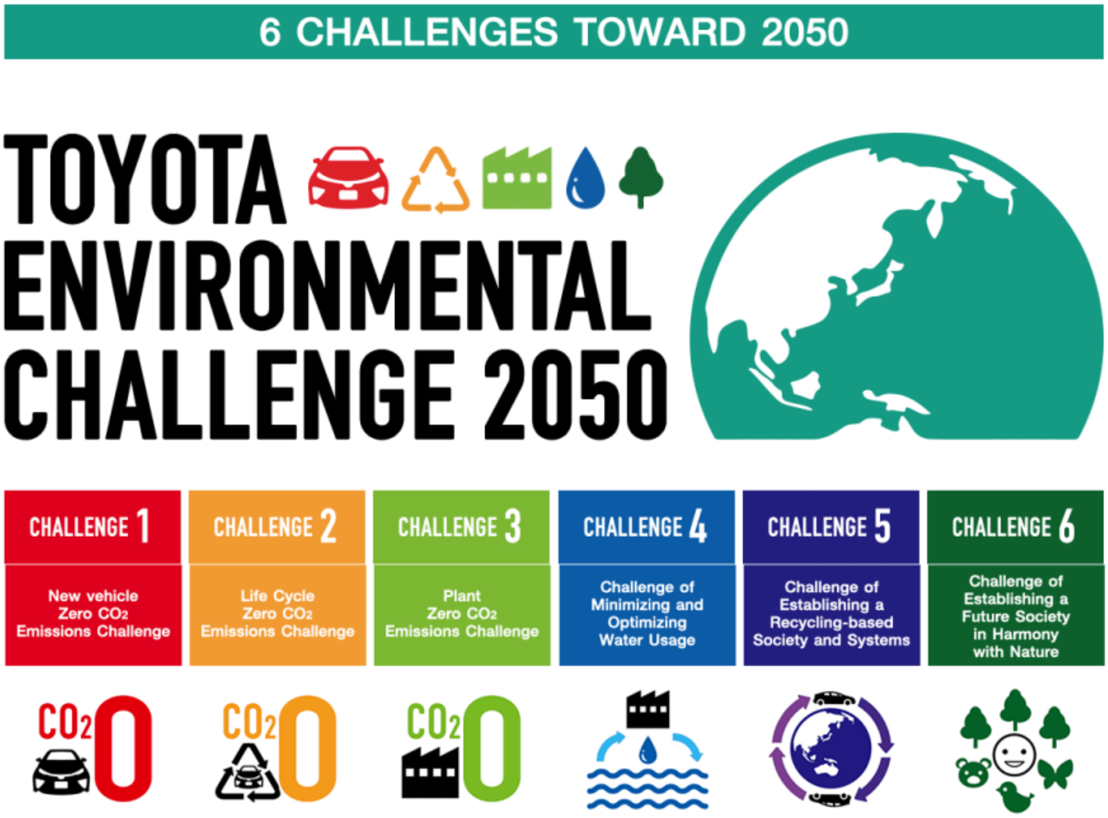


Figure 7. Toyota Environnemental Challenge 2050
Source : Internet, http://www.toyota-global.com/sustainability/environment/challenge2050/

This thesis will study energy saving measures in the primer painting booth (PB) during the painting process at the Toyota plant in France as part of Toyota's 2050 challenge three of plant zero CO_2 emissions. For that an energy audit will be carried out.

Different efforts have been made to reduce energy consumption in production facilities. However, the challenge is to find a way to introduce energy saving measures without compromising the manufacturing process and its quality.

2.3 Toyota Motor Manufacturing France

Toyota Motor Manufacturing France (TMMF) is located in Valencienne (France). It is one of the 9 manufacturing plants that Toyota owes in Europe. Its surface goes up to 233 hectares and a total of 3900 people work in the plant.

Its production started on 2001 and it is focussed on the Yaris model. Around 1020 Yaris are produced per day[1].

Figure 8 shows the distribution of the plant.

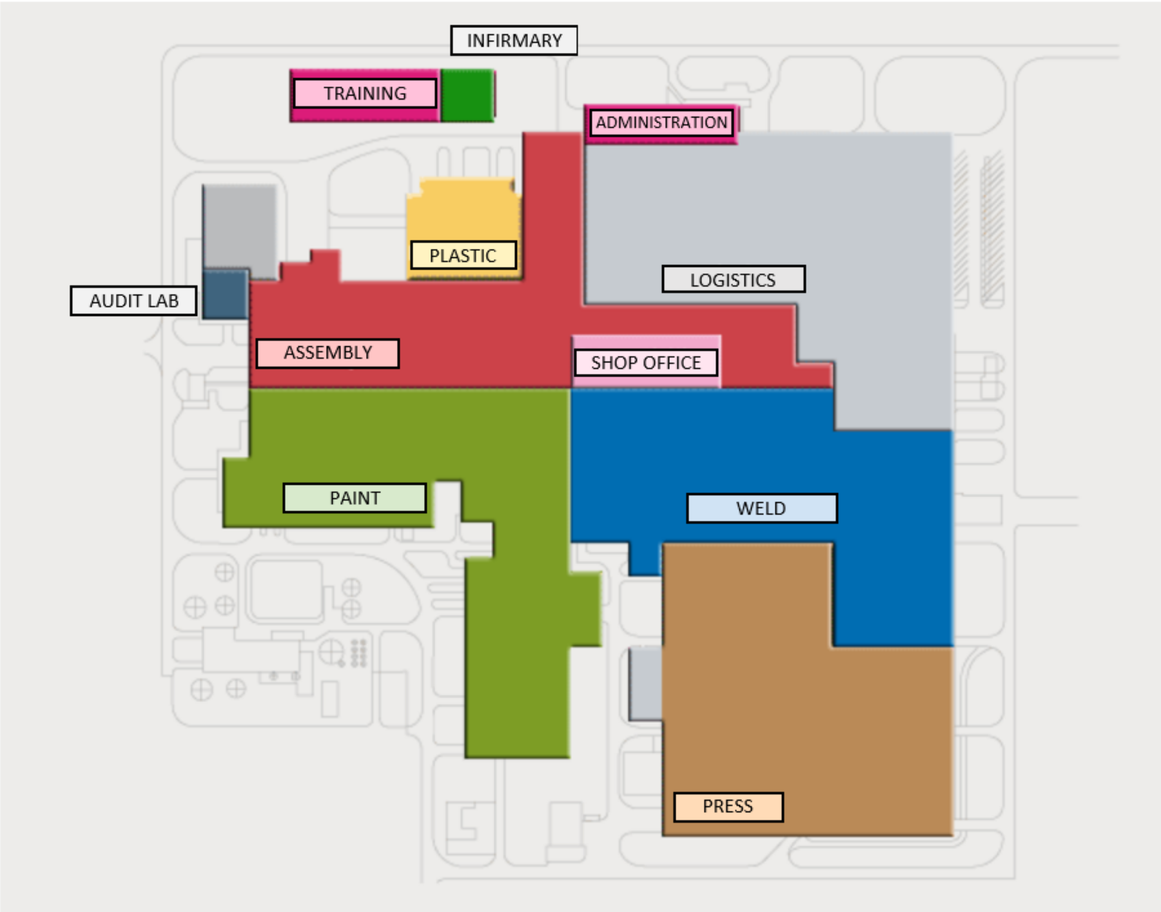


Figure 8. Shop distribution at TMMF
Source: Internet, http://tmmf.toyota-europe.com/process-fabrication

As Figure 8 shows, the plant is composed by seven main shops: paint, press, welding, plastic, assembly, logistics and administration.

[1] http://tmmf.toyota-europe.com/

Chapter 3

Energy Audit

3.1 Aim and objectives.

The energy audit that will be performed in the primer booth of the paint shop at TMMF will aim to identify possible opportunities to reduce the energy consumption for a more efficient utilization of its energy. Therefore, the main objectives are:

1. Carry out an energy analysis to have a deep understanding of how the energy at the paint booth is being used.

2. Propose and assess at economical and technical level possible improvements to establish an optimal order of their implementation.

3. Conduct a non- production study to reduce the energy that does not contribute to car production.

At the end, energy utilization across the primer booth should be understood and energy conservation measures should be introduced.

This thesis aims to contribute to challenge 3 of the Toyota Environmental Challenge 2050. Therefore, actions proposed to have a better energy management will target the CO_2 emissions of plants.

3.2 Methodology

In the following section the methodology that will be used to achieve the objectives will be described.

Figure 9 shows the approach that will be followed. This approach tries to establish a systematic procedure to make an energy audit, so it could be used no matter the shop or the equipment.

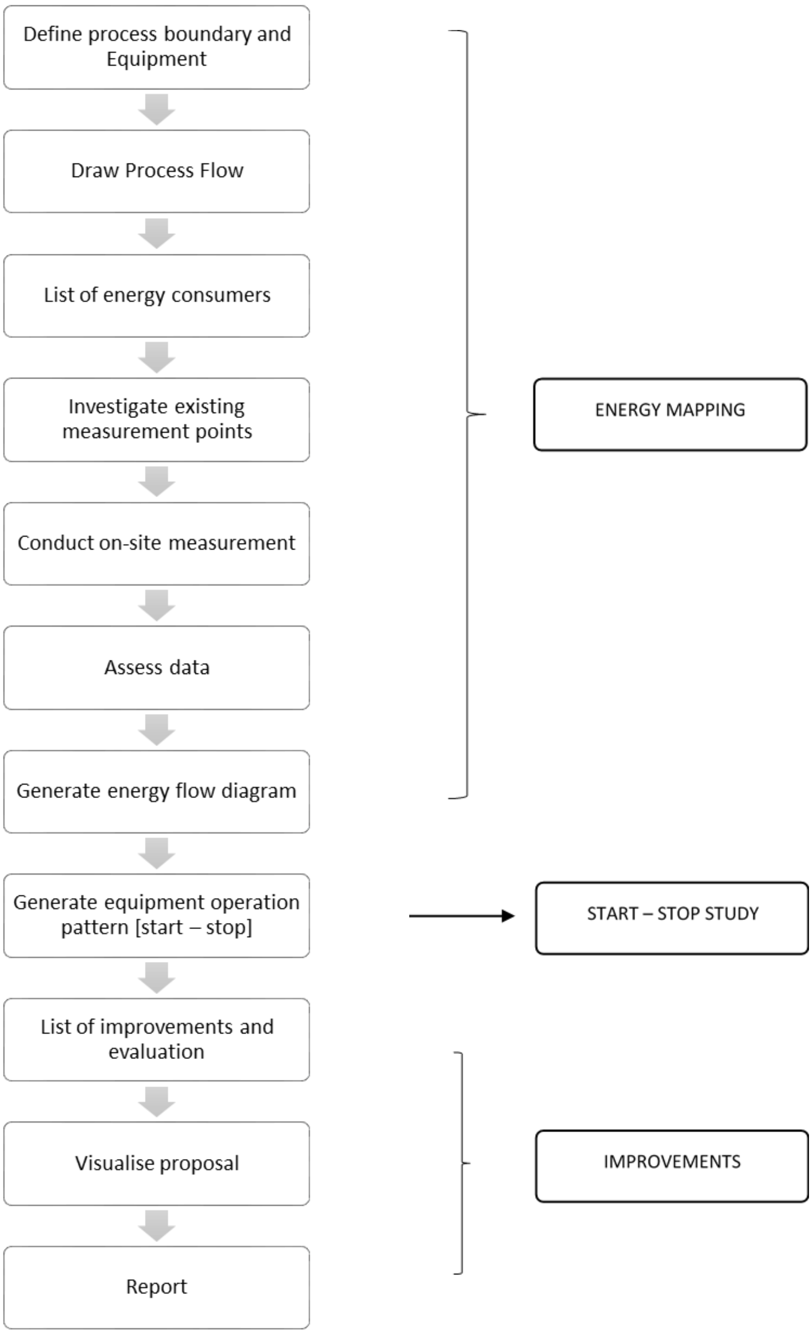


Figure 9. Methodology

Firstly, it is necessary to understand the energy consumption and breakdown of the process. For that reason, an Energy Mapping of the equipment will be carried out. This task will start by defining the scope of the energy study. It will continue by establishing the potential measurements points and by elaborating a plan to obtain the data from the equipment. Once all the data is gathered its assessment will take place. This stage of the audit will finish with an energy flow diagram that will help to visualise how the energy goes through the process and where the main losses are concentrate.

Finally, possible improvements will be listed and evaluated. This thesis will also make a detailed analysis on the Start Stop measures.

3.3 Process boundary and equipment.

When trying to reduce the energy consumption of a manufacturing plant a wide range of possibilities appear. That is why it is necessary to first define the scope of the energy audit. For this purpose, the energy usage of TMMF was evaluated.

As Figure 8 shows TMMF is composed by seven main shops: press, welding, plastic, paint, assembly, logistics and administration. All of them opened to potential energy savings. However, when talking about car manufacturing the painting process is claimed to be the highest energy consumer [FENG15], assumption that will be verified after the energy analysis.

In order to study the energy performance of each shop one year energy consumption data was gathered. The collection process was made through the PI System. This software was developed by OSISoft and allows to collect, asses and visualize ancient and current large amounts of data. This constant monitoring enables to learn from previous performance, to take more informed decisions and to prioritize tasks depending on specific needs.

In this case, it helped to choose the shop where to perform the energy audit. Using the electrical and natural gas consumption of each shop from 1/1/2017 to 1/1/2018 an energy breakdown of the plant was made. Figure 10 shows the results of the study.

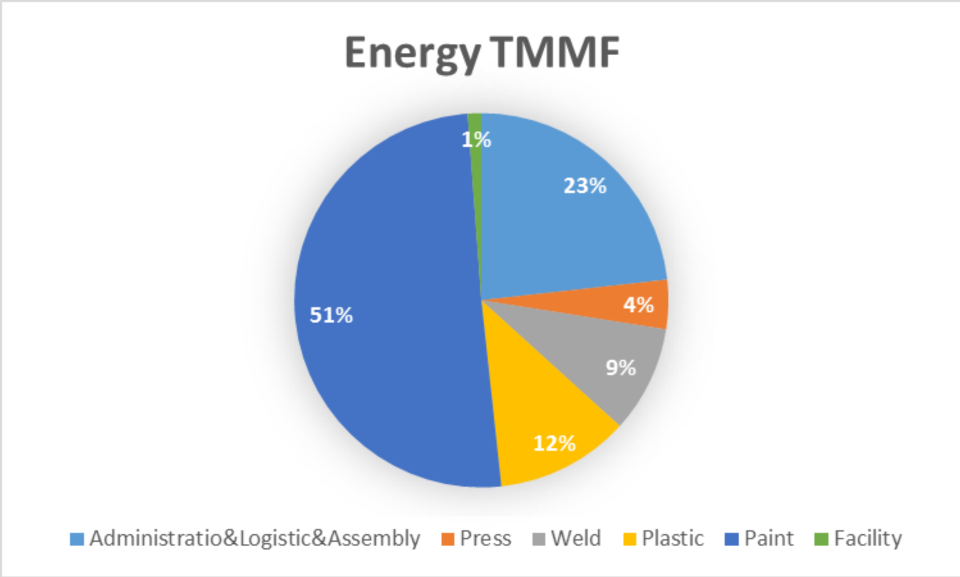


Figure 10. Energy breakdown of TMMF.

As expected the paint shop is the highest energy consumer. Therefore, the energy audit will be carried out there as its optimization could result in huge energy savings.

3.3.1 Painting process.

With an increasing global automobile demand, manufactures have to strive to exceed customer's expectations. Therefore, quality and appearance are key factors to bear in mind, being both highly dependent on the painting process [AKAF16].

So, the painting application not only does it give the car the protection to resist adverse conditions, but also its commercial attractiveness being very important when selling cars [AESS02]. For this reason, the painting process has become one of the most demanding factors of car manufacturing.

In order to achieve durable surfaces and meet the quality expectations a systematic coating process is followed. Figure 11 shows the coating process followed in car manufacturing [ARTI13].

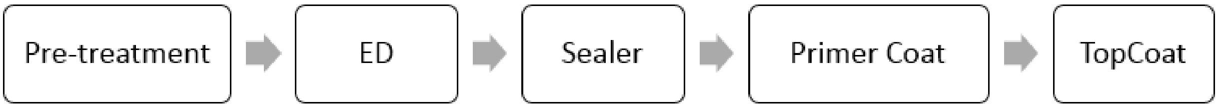


Figure 11. Coating process

This process is explained bellow:

Pre-treatment is the first phase in the painting application. It consists of chemically degreasing and cleaning the body car surface of rust and dirt remaining from the stamping and welding manufacturing stages. It ends with phosphating which provides protection as well as it enhances the adhesion of the next coats on the metal [FATH08].

Electrodeposition (ED) is a process that creates a uniform and complete layer on the car using electrical attraction that enables the painting to get to places where sprays do not penetrate. It is aimed to provide a corrosion and rust prevention layer [GOLD07].

The sealer is the third stage in the coating process and it is not applied everywhere. It mainly prevents air and water infiltrations. Additionally, it can act also as noise and rust protection. [AESS02].

The primer coat has different functions. Firstly, it smooths small scratches and imperfections from previous stages. Secondly, it ensures good bonding of the ED coat to the next coats. Finally, it offers weather and chipping resistance. In conclusion, it focusses on increasing paint durability [AKAF16]. The primer coat is applied in the primer booth.

The topcoat is the final step. It is composed of two coats: base and clear. On the one hand, the base coat gives the colour. On the other hand, the clear coat gives the gloss, the smooth and even the finish that results in the car visual appearance together with the final protection against environmental effects [GOLD07].

Regarding the primer and topcoat stages, painting development has played an essential role when reducing the volatile organic compounds (VOC) liberated during the painting process as they are a major hazard for the environment [HOLE__].

These five steps are very standardized in the industry. They are applied in a specific order and each of them have a particular functionality for the paint finishing [AKAF16]. Figure 12 shows the vehicle coating layers.

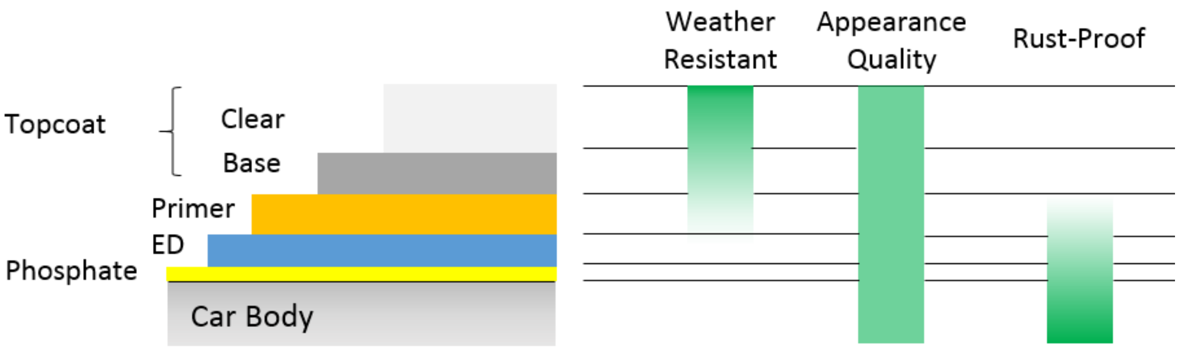


Figure 12. Vehicle coating layers [AKAF16]
Source: "Evolution of the Automotive Process—A Review", Akafuah, Nelson K., Sadegh Poozesh, Ahmad Salaimeh, Gabriela Patrick, Kevin Lawler, Kozo Saito, 2016

Considering the wide variety of possibilities when trying to reduce energy in the painting process this current thesis will focus on the process of applying the primer coat.

As mentioned before the primer coat is applied in the primer booth. Therefore, the energy audit will be performed on the primer booth.

3.4 Process Flow in the Primer Booth

Once it has been established that the process under study will be the primer booth it is necessary to understand how it works.

When applying the primer layer in the primer booth, it is necessary to have a good interaction between three main parts:

- Car
- Air flow
- Paint

Figure 13 shows a diagram of how each part behaves in the primer booth.

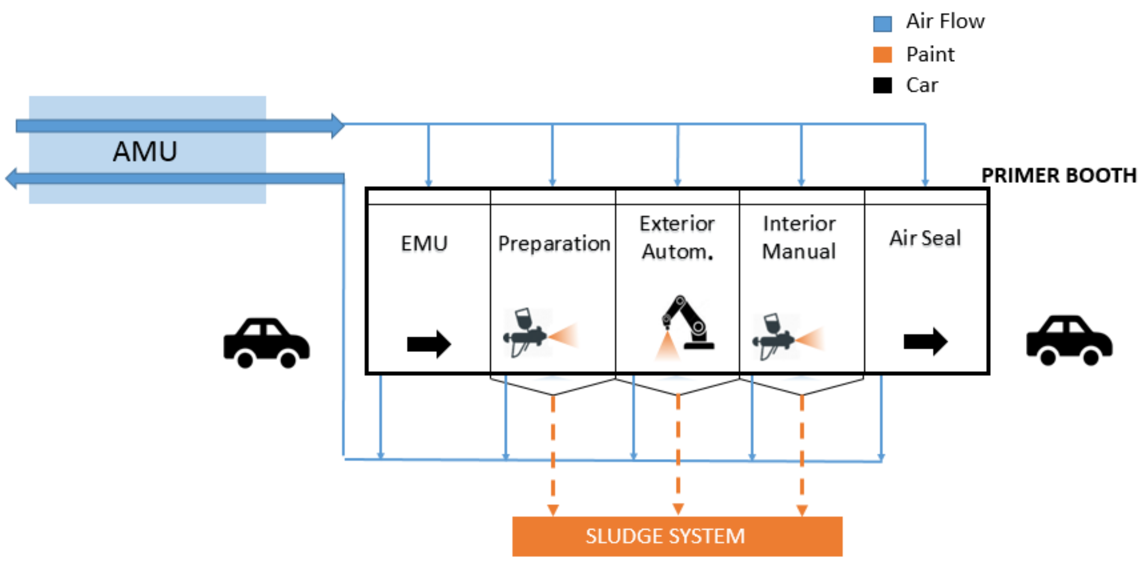


Figure 13. Primer paint booth flow

To start with, cars get into the primer paint booth. A paint booth is an enclosed room that protects the working environment from paint's particle matter and gasses [FENG15]. It consists of different steps that have to fulfil two main objectives. They have to guarantee visual quality as well as to ensure that the physical and technological requirements are met such as corrosion or chipping protection. For this purpose, the vehicle goes through five different processes in the primer booth.

Initially, the body is cleaned. This takes place in the EMU where there is an automatic cleaning system that makes rotate ostrich feather brushes assuring that there is no dirt accumulation on the body. In addition, there is an air system that eases the dirt particles separation off the body while constantly filtering the air.

Then the car is prepared for the manual and automatic painting. In other words, any dirt remaining is manually eliminated. Generally, for interior parts and areas that are difficult to access such as the door's interior or the luggage compartment, manual spray guns are used. On the contrary, for the car's exterior, robots are used. Due to large volumes of production it is not feasible to only use manual guns. Therefore, both painting methods complement each other.

Finally, the body goes through the air seal and the primer coat application finishes. This stage acts as a barrier between the oven and the painting booth, so the different airs do not mix.

In order for the primer coat phase to be over, it is necessary to dry the coat in the oven.

Table 2 gathers the initial data provided for the air flow of the primer paint booth

Parameter	EMU	Preparation	Exterior automatic	Interior manual	Air seal
Supply air flow rate [m³/h]	13,000.00	50,000.00	65,000.00	190,000.00	10,000.00
Chamber width [m]	6	10	12	24	3
Chamber length [m]	2.6	5.5	6	5.5	3.5
Airspeed [m/s]	0.2	0.25	0.25	0.4	0.1
Exhaust air flow rate [m³/h]	11,250.00	50,000.00	65,000.00	190,000.00	4,000.00

Table 2. Primer Paint Booth data

As for the air flow, it is highly related to the car paintwork's quality. To ensure it will be met it is necessary to closely control the air's temperature and humidity. As the painting process is mostly automatized there is no possibility to compensate any variation on the outside air's parameters in the booths, so it has to be done before. The Air make-up unit (AMU) is the system in charge of preparing and supplying the air to the booths. Additionally, it is the equipment that consumes the highest amount of energy.

When the outside air gets into the AMU, it is pre-heated in the heat exchanger. Afterwards, the heater increases its temperature above the recommended as it will lose some degrees while humidifying. Then, it is humidified, and it is discharged into the booths by the supply fans. In the end, the exhaust air stream is discharged with the exhaust fans while cooling in the heat exchanger.

To end with, the paint enters the booths through the paint robots or guns. Even though the ratio of attached paint to the car body is very high, there is still some that is over sprayed and has to be disposed of not only for quality reasons, but also for health and safety ones. This process is done with the sludge system.

3.5 Energy consumers in the Primer Booth.

After understanding how the primer booth works, data and information regarding energy consumption should be collected. In this section it will be described the equipment that needs to be measure or that will take part in the energy study.

As divided in section 2, the painting process' equipment will be classified in three categories:

1. AMU
2. Paint Booth
3. Paint Sludge System

Table 3 gathers the equipment involved in the primer paint booth process.

Equipment		Component	Number	Utility
AMU		Supply Fan	3	Electricity(E)
AMU		Exhaust Fan	3	Electricity
AMU		Spray Humidifier Pump	1	Electricity
AMU		Heat Recovery Motor	3	Electricity
AMU		Heat Recovery Cleaning Pump	1	Electricity
AMU		Heater	1	Natural gas (NG)
AMU		Anti-frost Heater Humidifier	3	Electricity
Paint Booth	EMU	Filter Fan	2	Electricity
Paint Booth	EMU	Blower	1	Electricity
Paint Booth	Preparation	Manual repair guns	4	Compressed Air (CA)
Paint Booth	Preparation	Lighting	70	Electricity
Paint Booth	Exterior Automatic	Robots	10	Electricity
Paint Booth	Exterior Automatic	Paint guns	10	Compressed Air
Paint Booth	Exterior Automatic	Lighting	27	Electricity
Paint Booth	Interior Manual	Paint guns	-	Compressed Air
Paint Booth	Interior Manual	Lighting	90	Electricity
Paint Sludge System		Circulation Pump	3	Electricity

Table 3. Primer Paint booth equipment

In the AHU there are six fans installed to supply and exhaust the air. In addition, there is also a heater and a humidifier to adjust the air to the tight temperature and humidity's range demanded by the painting application process. Moreover, the heat exchanger allows to preheat the outside air and cool the exhaust one avoiding any extra consumption. And in order to ensure proper functioning there is an anti-frost heater that prevents the humidifier water from freezing and a cleaning pump for the heat exchanger.

When analysing the primer paint booth all its stages use lighting. However, no all of them have the same equipment installed. On the one hand, there is a special ventilation system in the EMU consisting of two fans and one blower that supports the cleaning process of the body before applying the primer coat by ensuring a controlled and uncontaminated environment. On the other hand, preparation, interior manual and exterior automatic count with painting systems. The first two use paint guns while the last one uses robots. Mainly two types: 2 Nachi and 8 Kawasaki.

Finally, the paint sludge system recovery is the one in charge of the disposal of the over-sprayed painting. As commonly used in the sector, TMMF also uses wet scrubbers. Due to the high manufacturing volume, it is the most effective system. They are placed under the booths with painting systems and their task is to guarantee that the over sprayed droplets are transported outside the booths. In order to ensure a constant current of water there are three circulation pumps installed. Afterwards the extra paint is separated from the water and disposed of.

As shown in Table 3 electricity(E), compressed air (CA) and natural gas (NG) are the type of energy used. APPENDIX 1. Primer Booth Process Flow shows the complete primer booth diagram.

3.6 Investigation

Once all the equipment involved in the primer paint booth had been identified, several parameters were measured onsite in order to evaluate the system's performance. These measurements were afterwards complemented with calculations.

Regarding the onsite investigation, first technical data from the equipment was gathered. Table 4 shows the installed power of different equipment obtained onsite.

Equipment	Brand	Installed power [kW]
Exhaust Fan	Berlier	110
Spray Humidifier Pump	KSB	30
Sludge pump motor	VEM	30
Filter Fan	-	0.4

Table 4. Installed power onsite

Secondly, different measurements were carried out. As production changes from week days to weekend days, measurements for both periods were performed. Table 5 and Table 6 show the different measurements for week days.

Equipment	Motor	Measurements		
		Hertz [Hz]	Voltage[V]	Intensity[A]
Supply Fan	M1	45	304	118
	M2	45	304	120
	M3	45	302	120
Exhaust Fan	M1	50	361	176
	M2	50	361	173
	M3	50	361	172
Spray Humidifier Pump	-	30.3	138	32
Heat Recovery Motor	-	70	364	1.37

Table 5. Measurements week days 1

Equipment		Measurements [L/min]
Kawasaki	P1	520
	P3	550
	P5	520
	P7	520
	P8	530
	P6	570
	P4	560
	P2	520
NACHI		520
NACHI		520
Manual Repair Guns (Exterior Auto.)		520
Paint Guns (Interior Manual)		540

Table 6. Measurements week days 2

Table 7 shows measurement for weekend days.

Equipment	Motor	Measurements			
		Hertz [Hz]	Voltage[V]	Intensity[A]	Power[kW]
Supply Fan	M1	38	230	95	-
	M2	38	230	95	-
	M3	38	230	96	-
Exhaust Fan	M1	41	260	135	-
	M2	41	260	134	-
	M3	41	260	133	-
Spray Humidifier Pump	-	0	0	0	-
Heat Recovery Motor	-	70	364	1.37	-
Sludge Pump	-	-	-	-	22

Table 7. Measurements weekend days 1

From the data obtained two conclusions are obtained:

1. Robots and the spray humidifier pump do not work during weekends.

2. Supply and exhaust fans consume less during weekends.

This information will be later confirmed in the calculations section.

Finally, as not all the equipment was reachable to measure, some data was obtained from the electrical schematics and technical data sheets. Table 8 shows the data collected.

Equipment	Installed power[kW]
Supply Fan	90
Exhaust Fan	110
Heat Recovery Motor	1.5
Heat Recovery Cleaning Pump	4
Anti-frost heater humidifier	2.5
Air handling unit EMU	11

Table 8. Installed power data sheets

3.7 Calculations

In this section, calculations for the energy audit will be explained. The aim is to get each equipment's power consumption.

For this study it will be necessary to calculate the total energy, both from production (PT) and non-production (NPT) time. The first one includes the time when cars are being produced while the second ones refers to the time when there is no car production. However, during non-production time there could be still energy consumption.

Before calculations, data for the AMU's electricity and natural gas consumption was collected from the PI System. This research was based on information updated every fifteen minutes from 5/1/2017-5/1/2018. Both holidays and days with abnormal energy utilization were left out of the study. Information was organized weekly and Figure 14 shows the yearly average of every fifteen minutes of each week. The natural gas usage refers only to the primer while the electrical also includes base.

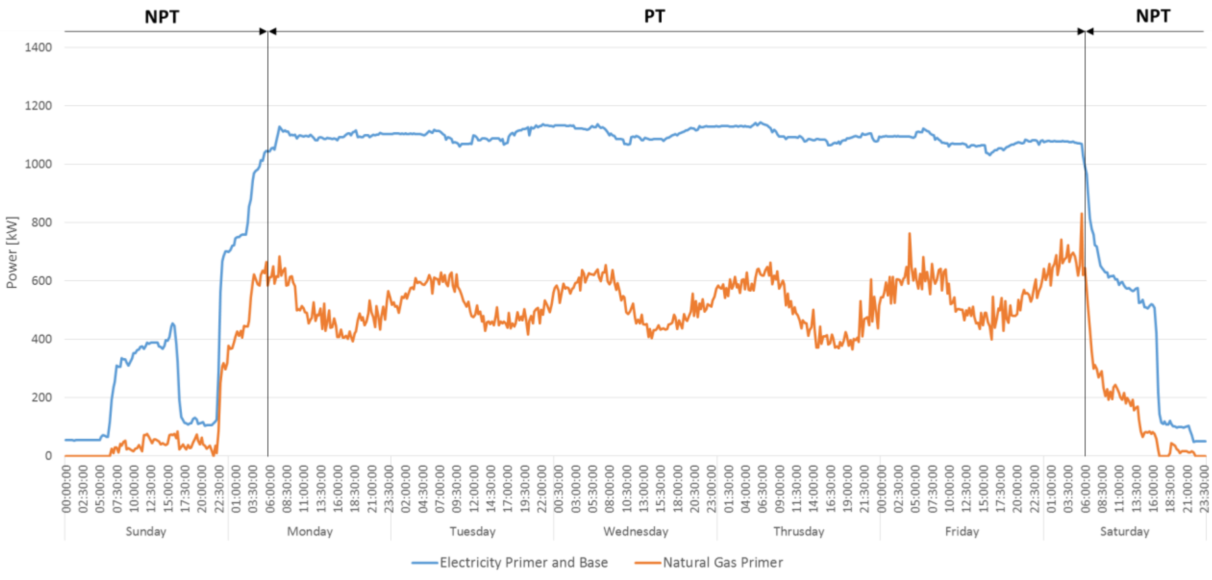


Figure 14. Electricity and natural gas consumption for a week.

From this figure, power calculations of the equipment are expected to be higher during production time than in non-production time.

3.7.1 Production time (PT)

This section will present calculations done to get the power consumption of the equipment during production time. The different utilities used in the AMU will be explained, starting with electricity, continuing with compressed air and finishing with natural gas.

In the production time power consumption was mainly calculated from the data obtained during onsite investigation, summarized in Table 5 and Table 6.

Firstly, calculations regarding the equipment consuming electricity were made.

As for the energy usage of the supply and exhausts fans, the spray humidifier pump and the heat recovery motors it was calculated as follow:

$$P[W] = \sqrt{3} \cdot U[V] \cdot I[A] \cdot \cos\varphi \qquad (1)$$

Table 9 shows the power consumption for each equipment. The cosφ has been estimated from previous studies.

Equipment	Motor	U [V]	I[A]	cosφ	P [kW]
Supply Fan	M1	304	118	0.85	53
	M2	304	120	0.85	54
	M3	302	120	0.85	53
Exhaust Fan	M1	361	176	0.85	94
	M2	361	173	0.85	92
	M3	361	172	0.85	91
Spray Humidifier Pump	-	138	32	0.85	6.1
Heat Recovery Motor	-	364	1.37	0.85	0.7

Table 9. Production calculations: electricity

All results will be considered except for the spray humidifier pump's. On the one hand, to simplify, an averaged power value will be used for the fans. On the other hand, as mentioned before in an automotive paint shop the AMU has to be constantly adjusting air's temperature and humidity parameters so quality conditions are met. Therefore, it is expected for the spray humidifier pump to not have a constant energy consumption. This energy fluctuations for the pump could be observed in Figure 14. Hence, the power calculated in Table 9 is not representative and an average will be used. This average was estimated to be a 60% of its installed power. A more visual explanation is given in Figure 15.

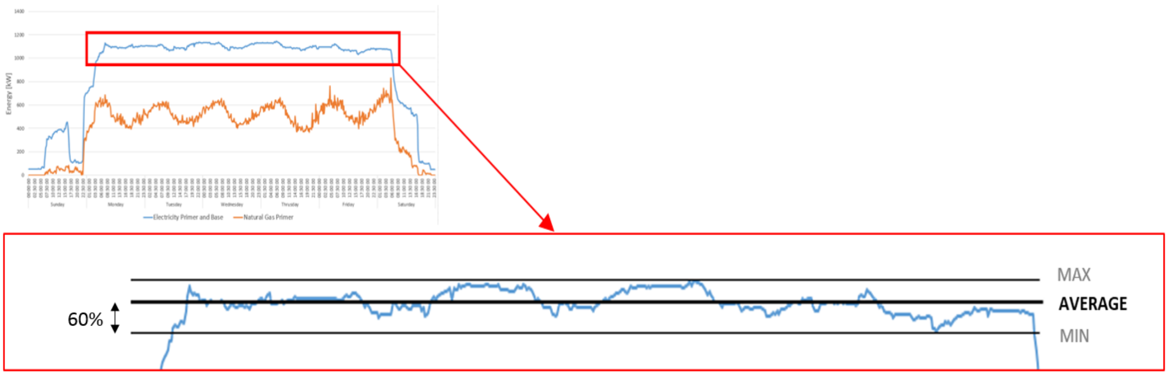


Figure 15. Detail of spray humidifier pump

The lighting's total electrical utilization was calculated from one fixture's energy consumption. Estimating it to be 60W the procedure is the following:

$$P = \text{One fixture's power} \cdot \text{number of fixtures} \quad (2)$$

Table 10 summarizes the lighting consumption.

Equipment	Number of lightings	Power [kW]
Preparation lighting	70	4.2
Exterior Automatic lighting	27	1.6
Interior Manual lighting	90	5.4

Table 10. Production calculations: lighting

Regarding the electrical consumption of the sludge pumps, even though the power was measured during the weekend, it will be assumed to be the same during week days.

To end with the electrical part of the study, the power consumption of the rest of the equipment was considered to be either its installed power shown in Table 4 and Table 8, for instance, the power of the air handling unit in the EMU and the filter fans, or cero, for example, the power of the heat recovery cleaning pump or the anti-frost heater humidifier as they are not used during production.

Having finished with the electrical calculations during production time, Table 11 shows the results obtained so far.

			Installed Power [kW]		Average demand			
Component	Number	Utility	Component	Total	Component		Total	
Supply Fan	3	E	90	270	53	[kW_e]	159	[kW_e]
Exhaust Fan	3	E	110	330	93	[kW_e]	279	[kW_e]
Spray Humidifier Pump	1	E	30	30	18	[kW_e]	18	[kW_e]
Heat Recovery Motor	3	E	1.5	4.5	0.7	[kW_e]	2.1	[kW_e]
Heat Recovery Cleaning Pump	1	E	4	4	0	[kW_e]	0	[kW_e]
Heater	1	NG				[kW_{th}]		[kW_{th}]
Anti-frost Heater Humidifier	3	E	2.5	7.5	0	[kW_e]	0	[kW_e]
Filter Fan	2	E	0.4	0.8	0.4	[kW_e]	0.8	[kW_e]
Air Handling Unit	1	E	11	11	11	[kW_e]	11	[kW_e]
Manual repair guns	4	CA				[kW_e]		[kW_e]
Lighting (Preparation)	70	E			4.2	[kW_e]	4.2	[kW_e]
Robots guns	10	CA				[kW_e]		[kW_e]
Lighting (Exterior Auto)	27	E	-	-	1.6	[kW_e]	1.6	[kW_e]
Paint guns		CA				[kW_e]		[kW_e]
Lighting (Interior Manual)	90	E	-	-	5.4	[kW_e]	5.4	[kW_e]
Circulation Pump	3	E	30	90	22	[kW_e]	66	[kW_e]

Table 11. Energy mapping electricity PT

Secondly, the compressed air flow consumption was converted into power through the TMMF ´s efficiency conversion factor for CA provided of 7.4 Nm^3/kWh for 6 barg and 15^0C. In order to apply this conversion factor, the robots' and paint gun's flow was recalculated to the normal state (P_N=1.013 bara and T_N=0^0C). The relation between the two flow rates is as follows:

$$q_N\left[\frac{Nm^3}{h}\right] = \frac{T_N[K]\cdot q\left[\frac{m^3}{h}\right]\cdot P[bara]}{P_N[bara]\cdot T[K]} \qquad (3)$$

For a more detailed explanation, calculations for the Kawasaki P1 Robot are presented below:

$$P_{P1} = q_N \left[\frac{m^3}{h}\right] \cdot \text{EfficiencyFactor} \left[\frac{kWh}{Nm^3}\right] =$$

$$= \frac{T_N[K] \cdot q \left[\frac{m^3}{h}\right] \cdot P[bara]}{P_N[bara] \cdot T[K]} \cdot \text{EfficiencyFactor} \left[\frac{kWh}{Nm^3}\right] =$$

$$= \frac{273.15K \cdot 520 \frac{L}{min} \cdot \frac{60min}{1h} \cdot \frac{1m^3}{1000L} \cdot 7bara}{1.013bara \cdot 288.15K} \cdot \frac{1}{7.4} \frac{kWh}{Nm^3} =$$

$$= \frac{273.15K \cdot 31.2 \frac{m^3}{h} \cdot 7bara}{1.013bara \cdot 288.15K} \cdot \frac{1}{7.4} \frac{kWh}{Nm^3} = 27.62kW$$

Extrapolating the calculations presented above to the rest of robots and paint guns, the power consumptions are shown in Table 12.

Robots		Flow [L/min]	Flow [m^3/h]	Flow [Nm^3/h]	Power [kW]
Manual Repair Guns(Preparation)		520	31.2	204.37	27.62
Paint Guns (Interior Manual)		540	32.4	212.23	28.68
Kawasaki	P1	520	31.2	204.37	27.62
	P3	550	33	216.16	29.21
	P5	520	31.2	204.37	27.62
	P7	520	31.2	204.37	27.62
	P8	530	31.8	208.30	28.15
	P6	570	34.2	224.03	30.27
	P4	560	33.6	220.10	29.74
	P2	520	31.2	204.37	27.62
NACHI		520	31.2	204.37	27.62
NACHI		520	31.2	204.37	27.62
TOTAL for robots		5330			283
Data		P*	7 bara	P_N	1.013 bara
		T**	288.15K	T_N	273.15K

Table 12. Production calculations: compressed air

*Pressure was converted from barg to bara by adding the atmospheric pressure (P_{atm}=1bara)
**Temperature was converted into Kelvin using: $T[K] = T[°C] + 273.15$

Summing up, calculations done so far are presented in Table 13.

			Installed Power [kW]		Average demand			
Component	Number	Utility	Component	Total	Component		Total	
Supply Fan	3	E	90	270	53	[kW_e]	159	[kW_e]
Exhaust Fan	3	E	110	330	93	[kW_e]	279	[kW_e]
Spray Humidifier Pump	1	E	30	30	18	[kW_e]	18	[kW_e]
Heat Recovery Motor	3	E	1.5	4.5	0.7	[kW_e]	2.1	[kW_e]
Heat Recovery Cleaning Pump	1	E	4	4	0	[kW_e]	0	[kW_e]
Heater	1	NG				[kW_{th}]		[kW_{th}]
Anti-frost Heater Humidifier	3	E	2.5	7.5	0	[kW_e]	0	[kW_e]
EMU Filter Fan	2	E	0.4	0.8	0.4	[kW_e]	0.8	[kW_e]
EMU blower	1	E	11	11	11	[kW_e]	11	[kW_e]
Manual repair guns	4	CA	-	-	-	[kW_e]	27.6	[kW_e]
Lighting (Preparation)	70	E	-	-	4.2	[kW_e]	4.2	[kW_e]
Robots guns	10	CA	-	-	-	[kW_e]	283	[kW_e]
Lighting (Exterior Auto)	27	E	-	-	1.62	[kW_e]	1.62	[kW_e]
Paint guns		CA	-	-	-	[kW_e]	28.6	[kW_e]
Lighting (Interior Manual)	90	E	-	-	5.4	[kW_e]	5.4	[kW_e]
Circulation Pump	3	E	30	90	22	[kW_e]	66	[kW_e]

Table 13. Energy mapping electricity and compressed air PT

Finally, for the natural gas calculations, the heater's flow for a year was obtained from the PI System, normalized by applying equation (3) and converted into power by using the gas' calorific value provided (10.37 kWh/Nm^3). When normalizing the gas' flow, TMMF pressure and temperature conditions for NG were used. Table 14 shows the data used for the calculations.

Data	
Pressure	1.25 barg
Temperature	283.15 K
Gas Flow 3/1/2017	2094931 m^3
Gas Flow 3/1/2018	2379160 m^3

Table 14. Production calculations: natural gas

The natural gas' calculations are presented below:

$$P = \text{Gas Flow}\left[\frac{\text{Nm}^3}{\text{yr}}\right]\cdot \text{Calorific value}\left[\frac{\text{kWh}}{\text{Nm}^3}\right] =$$

$$= (2379160 - 2094931)\frac{\text{m}^3}{\text{yr}}\cdot\frac{273.15\text{K}\cdot 1.25\text{bara}}{283.15\text{K}\cdot 1.013\text{bara}}\cdot 10.37\frac{\text{kWh}}{\text{Nm}^3} =$$

$$= 338340\frac{\text{Nm}^3}{\text{yr}}\cdot 10.37\frac{\text{kWh}}{\text{Nm}^3} = 3508588\frac{\text{kWh}}{\text{yr}} =$$

$$= 3508.6\frac{\text{MWh}}{\text{yr}}$$

As these calculations take into account the gas' flow for a year both production and non-production time are included.

So, after all the calculations Table 15 contains data collected for PT.

			Installed Power [kW]		Average demand			
Component	Number	Utility	Component	Total	Component		Total	
Supply Fan	3	E	90	270	53	[kW_e]	159	[kW_e]
Exhaust Fan	3	E	110	330	93	[kW_e]	279	[kW_e]
Spray Humidifier Pump	1	E	30	30	18	[kW_e]	18	[kW_e]
Heat Recovery Motor	3	E	1.5	4.5	0.7	[kW_e]	2.1	[kW_e]
Heat Recovery Cleaning Pump	1	E	4	4	0	[kW_e]	0	[kW_e]
Heater	1	NG	-	-	-	[kW_{th}]	-	[kW_{th}]
Anti-frost Heater Humidifier	3	E	2.5	7.5	0	[kW_e]	0	[kW_e]
EMU Filter Fan	2	E	0.4	0.8	0.4	[kW_e]	0.8	[kW_e]
EMU blower	1	E	11	11	11	[kW_e]	11	[kW_e]
Manual repair guns	4	CA	-	-	-	[kW_e]	27.6	[kW_e]
Lighting (Preparation)	70	E	-	-	4.2	[kW_e]	4.2	[kW_e]
Robots guns	10	CA	-	-	-	[kW_e]	283	[kW_e]
Lighting (Exterior Auto)	27	E	-	-	1.62	[kW_e]	1.62	[kW_e]
Paint guns		CA	-	-	-	[kW_e]	28.6	[kW_e]
Lighting (Interior Manual)	90	E	-	-	5.4	[kW_e]	5.4	[kW_e]
Circulation Pump	3	E	30	90	22	[kW_e]	66	[kW_e]

Table 15. Energy mapping for PT

All the consumption explained in this section is called normal mode (NM) and it is characterized for fans running at normal speed, the gas burner controlling the air's temperature among 19^{0}C - 26^{0}C and the spray humidifier pump running. On the contrary, when fans are working at reduced speed, the gas burner controls the temperature to 18^{0}C and the spray humidifier is stopped is called saving mode (SM). This mode is set during non-production time (NPT). Table 16 show the possible modes for the equipment.

	Supply&Exhaust fan	Gas burner	Spray Humidifier
Normal Mode	Run at normal speed	Control temp [19-26] ^{0}C	Run
Saving Mode	Run at reduce speed	Control temp 18^{0}C	Stop
Stop Mode	Stop	Stop	Stop

Table 16. Mode explanation

3.7.2 Non-production time (NPT)

This section contains information about the calculations followed to estimate the power consumption of the equipment in the primer paint booth during non-production time.

Non-production is called to the time when cars are not being manufactured. It usually happens during the weekend. In order to analyse its power consumption, it has been divided in different time frames. In this context, power has been averaged over the different time ranges. In other words, a weighted average has been computed of the equipment's power in each stage, according to the hours each stage lasts.

Firstly, it is going to be explained how NPT is distributed in the plant. Then, it is going to be calculated the energy usage during each NPT's time frame. To finish with, the weighted average of the energy will be computed.

TMMF production's time is divided in three shifts from Monday to Friday. Table 17 shows the morning, evening and night schedules.

Production Time (PT)		
	Start	Stop
Shift 1 - Morning	05:30:00	13:00:00
Shift 2 - Evening	14:00:00	21:30:00
Shift 3 - Night	22:00:00	05:30:00

Table 17. TMMF shifts' schedule

From this information, NPT is considered to start when Friday's night shift ends, meaning, at Saturday 5:30am and to finish when the Monday morning starts, meaning, at Monday

5:30am. From the AMU's electricity and natural gas consumption (see Figure 14) five stages could be differentiated, ordered as they happen:

- AMU at full power during NPT: although PT is over the AMU is still working at normal mode probably because it is necessary to do over time.

- Saturday maintenance work: the equipment reduces its consumption. Maintenance work is being performed in the booths. Afterwards the energy consumption stops.

- Sunday maintenance work: energy usage is registered even though there are no cars being manufactured due to the maintenance work being performed in the booths.

- Sunday start-up: equipment starts running again but not at normal mode. This stage is used to have the equipment fully operating when the first shift starts.

- AMU at full power during NPT: even though PT has not started yet, the AMU is operating at normal mode. During this stage trials are being carried out to assure that everything is working properly.

All this information is better detailed in Table 18 and in Figure 16.

		Schedule				
		Start		End		Hours [h]
1	AMU at full power during NPT	Saturday	05:30	Saturday	06:30	1
2	Saturday Maintenance work	Saturday	06:30	Saturday	16:30	10
	Gap	Saturday	16:30	Sunday	06:30	14
3	Sunday Maintenance work	Sunday	06:30	Sunday	16:30	10
	Gap	Sunday	16:30	Sunday	22:30	5.5
4	Sunday start-up	Sunday	22:00	Monday	03:00	5
1	AMU at full power during NPT	Monday	03:00	Monday	05:30	2.5
	TOTAL					48

Table 18. NPT stages

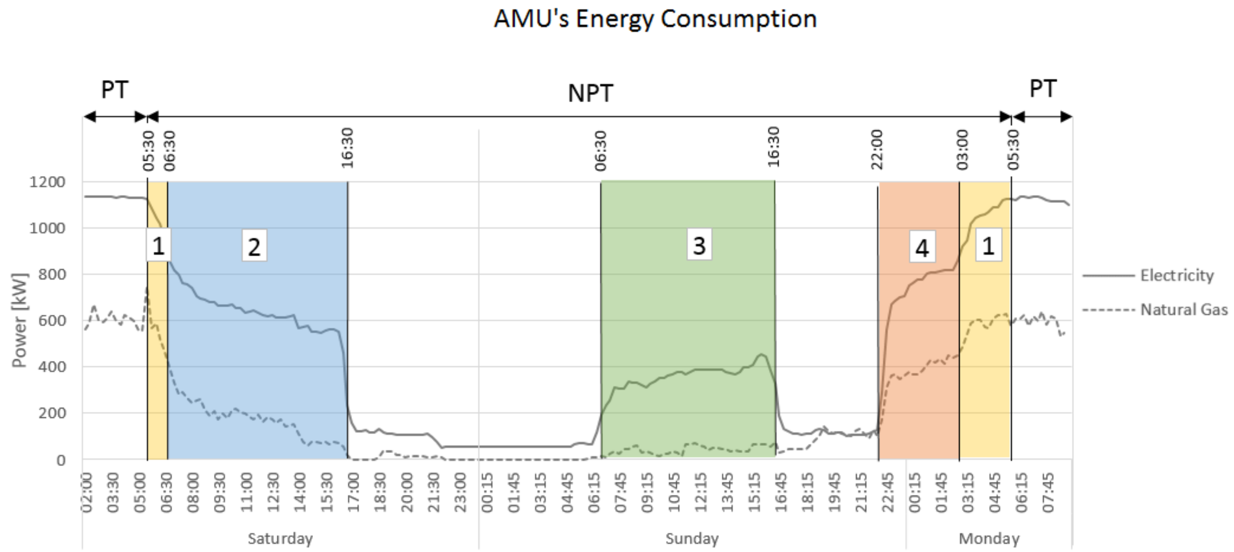


Figure 16. NPT stages

Once NPT schedule has been established, it is going to be calculated the power the equipment is using during each stage. For this purpose, Table 19 differentiates when equipment is in normal mode (NM) or saving mode (SM).

		Mode
1	AMU at full power during NPT	NM
2	Saturday Maintenance work	SM
	Gap	Stopped
3	Sunday Maintenance work	SM
	Gap	Stopped
4	Sunday start-up	SM
1	AMU at full power during NPT	NM

Table 19. Mode during NPT

In this section, only calculations regarding electrical and natural gas consumption will be made as there is no consumption of compressed air during NPT because robots and paint guns are not working.

Basing calculations on data summarized in Table 7 and following equation (2), power consumption for fans for saving mode was calculated. Table 20 shows the results obtained.

Equipment	Motor	U [V]	I[A]	cosφ	P [kW]
Supply Fan	M1	230	95	0.85	32
	M2	230	95	0.85	32
	M3	230	96	0.85	33
Exhaust Fan	M1	260	135	0.85	52
	M2	260	134	0.85	51
	M3	260	133	0.85	51

Table 20. Power consumptions fans for SM

Regarding the sludge system, from stage 2 to 4, only one pump is working out of the three that the system has.

As for the rest of the equipment, measurements could not be carried out and discussions with the weekend maintenance team were arranged. From these, useful information was obtained and detailed as follows:

1. The heat recovery motor only works when the AMU does.

2. The spray humidifier pump is stopped during NPT. As mentioned before, during production air's temperature and humidity have to be closely controlled. However, when cars are not being manufactured only temperature is to assure workers' comfort while performing maintenance activities in the booths.

3. The EMU blower is stopped when finishing PT.

4. The lighting and the EMU filter fan are assumed to be operating as in PT.

As for the heater's consumption during each NPT's time frame, a simulation was carried out in order to get the most accurate value. Due to the manual operation of the heater, values obtained from PI System were not representative. Gathering all the information for NPT, Table 21 summarizes the results obtained.

	AMU at full power**	Saturday Maintenance work**		Sunday Maintenance work**		Sunday start-up**	AMU at full power**
Hours [h]	1	10	14	10	5.5	5	2.5
Component	Total power Consumption [kW]						
Supply Fan*	159	32·3=96	0	96	0	96	159
Exhaust Fan*	279	51·3=153	0	153	0	153	279
Spray Humidifier Pump	15	0	0	0	0	0	0
Heat Recovery Motor	2.1	2.1	0	2.1	0	2.1	2.1
Heat Recovery Cleaning Pump	-	-	-	-	-	-	-
Heater	447	162.8	-	162.8	-	162.8	447
Anti-frost Heater Humidifier	-	-	-	-	-	-	-
Filter Fan	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Air Handling Unit	11	0	0	0	0	0	11
Manual repair guns	0	0	0	0	0	0	0
Lighting (Preparation)	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Robots guns	0	0	0	0	0	0	0
Lighting (Exterior Auto)	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Paint guns	0	0	0	0	0	0	0
Lighting (Int. Manual)	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Circulation Pump	66	22	22	22	22	22	66

Table 21. Results for NPT

*For fan's consumption during NPT an average of the three motors was used.
**Colours follow same categorization as in Table 18

As shown in Table 21 energy consumption associated with only the fans is significant. For that reason, in order to check that calculations have been done correctly, a quick calculation will be done using PT and NPT calculations and measurements.

AMU's fans are centrifugal fans and have to follow the affinity laws. These laws relate wheel velocity(n) with its power consumption(P) as follows:

$$\frac{P_{PT}}{P_{NPT}} = \left(\frac{n_{PT}}{n_{NPT}}\right)^3 \cdot \left(\frac{d_{PT}}{d_{NPT}}\right)^5 \qquad (4)$$

So, applying equation (4) to the supply fan data:

$$\frac{P_{PT}}{P_{NPT}} = \frac{53}{32} = 1.65$$

$$\frac{{n_{PT}}^3}{{n_{NPT}}^3} = \frac{45^3}{38^3} = 1.66$$

$$d_{PT} = d_{NPT}$$

$$1.65 \approx 1.66$$

Repeating calculations with the exhaust fan's data:

$$\frac{P_{PT}}{P_{NPT}} = \frac{93}{51} = 1.82$$

$$\frac{{n_{PT}}^3}{{n_{NPT}}^3} = \frac{50^3}{41^3} = 1.81$$

$$d_{PT} = d_{NPT}$$

$$1.82 \approx 1.81$$

From these results we can conclude that calculations and measurements match as expected.

Once power usage for each NPT time frame has been estimated, the next step is to compute the weighted average over the duration of each time frame. An example with supply fan's values will be given below:

$$P_{NPT}^{\text{Supply fan}} = \frac{P_1 \cdot h_1 + P_2 \cdot h_2 + P_{Gap} \cdot h_{Gap} + P_3 \cdot h_3 + P_4 \cdot h_4}{h_{NPT}} =$$

$$= \frac{159 \cdot (1 + 2.5) + 96 \cdot 10 + 0 \cdot (14 + 5.5) + 96 \cdot 10 + 96 \cdot 5}{48} = 61.6 \text{ kW}$$

The formula's subscripts follow Table 18 time categorization.

Extrapolating the calculations presented above to the rest of the PB's equipment, the power consumptions are shown in Table 22.

Equipment	Component	Power average NPT [kW]
AMU	Supply Fan	62
	Exhaust Fan	100
	Spray Humidifier Pump	1
	Heat Recovery Motor	1
	Heat Recovery Cleaning Pump	0
	Heater	117
	Anti-frost Heater Humidifier	0
EMU	Filter Fan	1
	Air Handling Unit	2
Preparation	Manual repair guns	0
	Lighting	4
Exterior Automatic	Robots	0
	Robots guns	0
	Lighting	2
Interior Manual	Paint guns	0
	Lighting	5
Sludge System	Circulation Pump	25

Table 22. Average power consumption NPT

3.7.3 Energy Mapping

Energy Audits study how energy is used to identify opportunities to save it. Therefore, to have a better understanding of the primer booth's consumption, calculations from previous sections will be transform from power(kW) to energy(kWh).

The procedure is as it follows:

$$E[kWh] = Power[kW] \cdot Consumption\ time[h] \quad (5)$$

As explained before, to carry out the energy study of the PB, time has been divided into production time (PT) and non-production time (NPT), lasting each time period 120 hours and 48 hours respectively for a week. Figure 17 shows the primer booth's schedule.

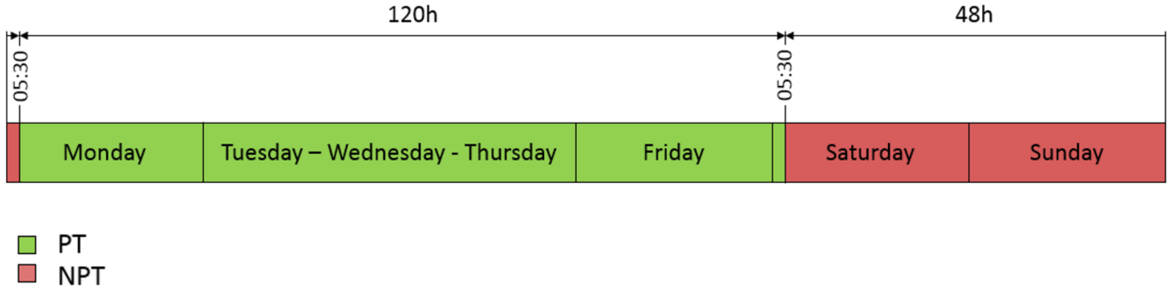


Figure 17. Primer Booth's schedule

Energy calculations will also follow the above schedule. An example will be given for the supply fans. Table 23 presents data that will be used for them. Power consumption represents the power consumption of the three fans, see APPENDIX 2. Data Energy Mapping.

	PT	NPT
Power [kW]	159	62
Time [h/week]	120	48

Table 23. Data for Supply fans

Using equation (5) and assuming that a year has 48 weeks, so holidays and shutdowns are not considered, the total energy consumption of the supply fans for a year is presented below:

$$E^{Supply\ fans} = P_{PT} \cdot Time_{PT} + P_{NPT} \cdot Time_{NPT} =$$

$$= \left(159\text{kW} \cdot 120 \frac{\text{h}}{\text{week}} + 62\text{kW} \cdot 48 \frac{\text{h}}{\text{week}}\right) \cdot 48 \frac{\text{weeks}}{\text{year}} = 1058688 \frac{\text{kWh}}{\text{year}} =$$

$$= 1058.6 \frac{\text{MWh}}{\text{year}}$$

Extrapolating the above calculation procedure to the rest of the equipment in the primer booth, the total energy consumption for a year is shown in Table 24.

Component	Average Power PT [kW]	PT hours per week [h/week]	Average Power NPT [kW]	NPT hours per week [h/week]	Weeks per year [week/year]	Total Energy consumption [MWh/year]
Supply Fan	159	120	62	48	48	1059
Exhaust Fan	279	120	100	48	48	1837
Spray Humidifier Pump	18	120	4	48	48	107
Heat Recovery Motor	2.1	120	1	48	48	14
Heat Recovery Cleaning Pump	0	0	0	48	48	0
Heater*	-	120	117	48	48	3509
Anti-frost Heater Humidifier	0	0	0	48	48	0
Filter Fan	0.8	120	1	48	48	7
Air Handling Unit	11	120	1	48	48	66
Manual repair guns**	27.6	109.25	0	48	48	145

Lighting (Preparation)	4.2	120	4	48	48	33
Robots guns**	283	109.25	0	48	48	1484
Lighting (Exterior Auto)	1.62	120	2	48	48	14
Paint guns**	28.6	109.25	0	48	48	150
Lighting (Interior Manual)	5.4	120	5	48	48	43
Circulation Pump	66	120	25	48	48	438

Table 24. Energy consumption for PB

*Total heater's energy was computed in section Production time (PT).
**For robots and paint guns pause time during shifts has been subtracted, a total of 10.75h/week.

As far as it concerns the energy audit, calculations are finished. Nevertheless, as this thesis aims to be part of the Toyota Environmental Challenge for 2050, in this section the CO_2 emissions of the primer booth will be also conducted.

To start, it is defined the conversion factor for CO_2 emissions and the electricity and natural gas cost ratio as it will be used later in this thesis. These factors vary from country and from type of energy used. Hence, the electricity factors will differ from the natural gas factors for both emissions and cost. Table 25 presents these factors for the Toyota manufacturing plant in France.

	Natural Gas	Electricity
CO_2 emission factor [tonCO_2/MWh]	0.183	0.035
$Cost_{Electricity}/Cost_{NaturalGas}$	1.95	

Table 25. TMMF's CO_2 and cost's factors

To continue, these factors are applied to the energy calculated and presented in Table 24. To finish, Table 26 contains the results for each equipment.

Component	Total Energy consumption per year [MWh]	CO_2 Emissions [tonCO_2/MWh]
Supply Fan	1059	37
Exhaust Fan	1837	64
Spray Humidifier Pump	113	4
Heat Recovery Motor	14	1
Heat Recovery Cleaning Pump	0	0
Heater	3509	642
Anti-frost Heater Humidifier	0	0
Filter Fan	7	0
Air Handling Unit	66	2
Manual repair guns	145	5
Lighting (Preparation)	33	1
Robots guns	1484	52
Lighting (Exterior Auto)	14	0
Paint guns	150	5
Lighting (Interior Manual)	43	2
Circulation Pump	438	15

Table 26. Emission results

In conclusion, after the energy study the primer booth consumes a total of:

- Energy: 8906 MWh/year
- Emissions: 831 tonCO_2/MWh

Once it is known how energy is used in the primer booth, the next step is to propose and evaluate potential energy saving measures.

Chapter 4

Improvements

Energy Audits require collecting, analysing and assessing relevant information of a plant in order to suggest possible improvements that could result in energy saving measures.

There are six types of measure that could be implemented:

1. Eliminate: improvements will be included in this category if after the energy study, equipment or processes with no useful purposes are detected and supressed.

2. Repair: it includes opportunities that save energy by fixing the current condition of an equipment.

3. Stop: it refers to actions that involve changing the on and/or off operation of an equipment.

4. Reduce: it considers measures regarding the decrease of the value of parameters that affects the equipment energy utilization.

5. Pick up: it includes any measure that deals with the reuse of a utility.

6. Change: it involves actions by which an equipment is replace by a more efficient one.

Although all measures included in these six categories would save energy, not all of them require the same investment. For this reason, there is a more general categorization:

- Energy Conservation: Items related with behavioural matters. They aim to get the best operation and maintenance. Generally, they are no cost or low cost to implement. Eliminate, repair, stop, reduce and pick up actions are included in this category

- Energy Efficiency Improvement: Items that require physical modifications of the equipment. They aim to get the best efficient technology. Moreover, they normally require big investment. Change actions are included in this category.

In order to increase energy efficiency in the primer booth, Table 27 presents the opportunities detected for energy saving.

Activity	Category		Idea
Energy Conservation (Best Operation and maintenance)	Stop	1	Stop sludge pumps when the AMU is off or in SM
		2	Start supply/exhaust fan late after production
	Reduce	3	Optimize temperature and humidity set points
		4	Reduce booth air speed
Energy Efficiency Improvement (Best efficient technology)	Change	5	Replace supply/exhaust fans with higher efficiency
		6	Convert to LED lighting at booth

Table 27. Improvements list

Due to the low investment, energy conservation measures are the ones implemented first. Later in this thesis energy and CO_2 savings will be presented for every proposed measure. In addition, a more detailed explanation will be provided for actions in the Stop and Change category.

At the end of this thesis a report for each improvement is presented.

4.1 Start Stop

Even though technological changes in equipment improve energy conservation, changes in its operation pattern could also have a great impact. APPENDIX 3. Start Stop Pattern shows the operational behaviour of the equipment in the primer booth.

Due to the high competitiveness presented in the European car manufacturing market, start stop procedure for the equipment during the week days (production time) has been deeply studied already. Therefore, the targeting time frame that will be assessed to introduce energy saving measures in this thesis will be the weekend (non-production time).

As explained in section Non-production time (NPT), the largest energy consumers during the weekend in the primer booth are the AMU and the sludge pumps. Hence, this section will focus on its operational behaviour.

4.1.1 AMU

In order to find possible improvements in the operational procedure of the AMU, first it is necessary to understand how it works.

Figure 18 shows the energy consumption for the AMU during non-production time.

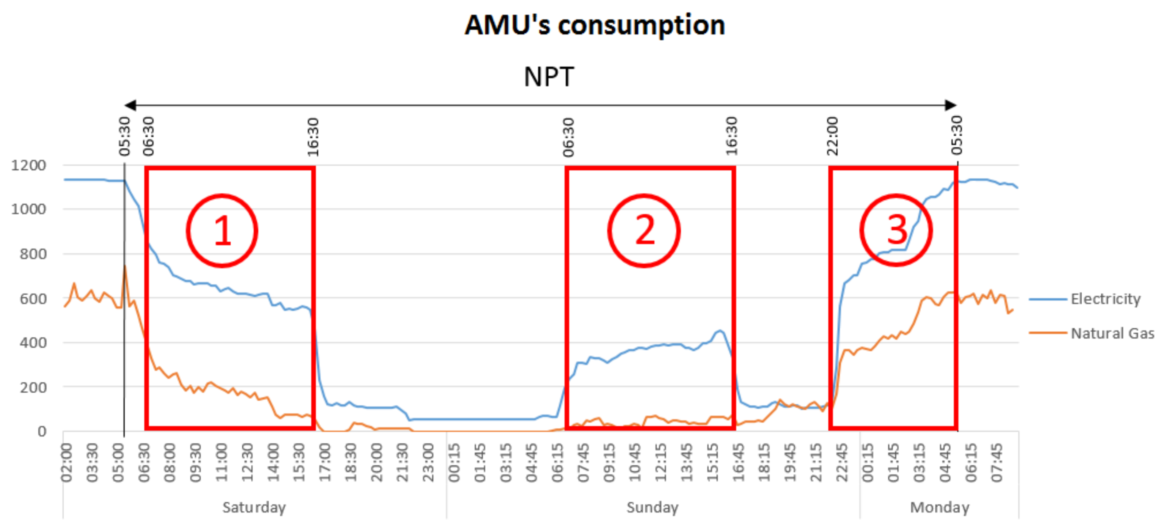


Figure 18. AMU’s consumption during NPT

Highlighted in red is the energy utilization that will be challenged during this study. Having already studied the weekend time in section Non-production time (NPT), Figure 19 presents a summary of the findings.

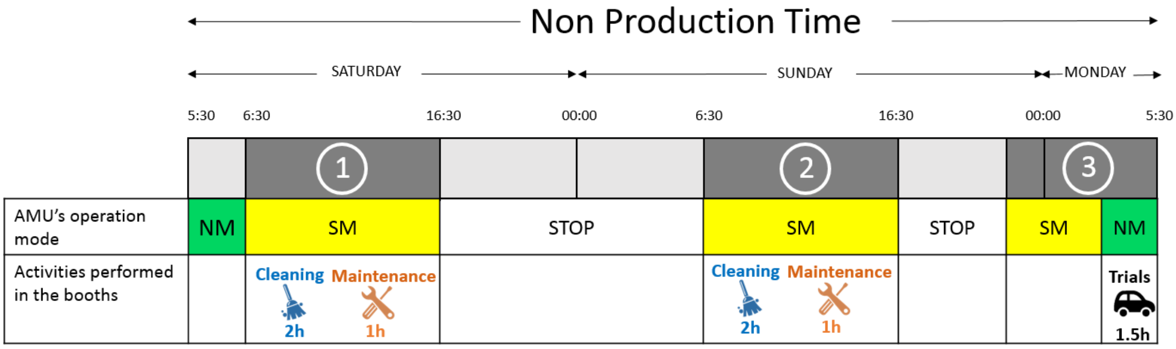


Figure 19. AMU findings for NPT

For further clarification, SM and NM correspond with AMU's saving and normal mode respectively, both explained in Table 16. Moreover, period classification is the same as in Figure 19.

The explanation will be divided in three parts. First, total energy consumption of the AMU for each period will be presented. Then, periods 1 and 2 will be explained and finally period 3 will be analysed.

In order to perform a comparative analysis between current conditions and proposed savings, it is necessary to know how much energy and CO_2 the AMU is now consuming in each NPT period. Table 28 presents the AMU current consumption.

Regarding all calculations made in this section, power data was obtained from APPENDIX 2. Data Energy Mapping, energy consumption was computed using equation (5) and CO_2 emissions were calculated with factors presented in Table 25.

	Number of equipment	Power NM [kW]	Power SM [kW]	Total Power [kW]							TOTAL PRIMER BOOTH
				NM	SM	Stop	SM	Stop	SM	NM	
Supply Fan	3	53	32	159	96	0	96	0	96	159	
Exhaust Fan	3	93	51	279	153	0	153	0	153	279	
Spray Humidifier Pump	1	15	0	15	0	0	0	0	0	15	
Heat Recovery Motor	3	0.7	0.7	2.1	2.1	0	2.1	0	2.1	2.1	
Heater	1	447	163	447	163	0	163	0	163	447	
Hours [h]				1	10	-	10	-	5	2.5	
Energy Consumption Electricity [MWh/yr]				22	121	0	121	0	60	55	378
Energy Consumption NG [MWh/yr]				21	78	0	78	0	39	54	270
Energy Consumption Total [MWh/yr]				43	199	0	199	0	99	108	**648**
CO_2 Consumption [ton/yr]				5	19	0	19	0	9	12	**63**

Table 28. AMU initial consumption.

Having explained AMU's initial consumption, now energy consumption for each period will be challenged.

Presently, periods 1 and 2 correspond with the weekend shift which lasts from 6:30 to 16:30, both on Saturday and on Sunday. Studying the activities performed during this shift, they could be classified in:

- Cleaning: performed by an external company. Its activity involves the cleaning of the floor and windows of the booths as well as the robots covers.

- Maintenance: performed by TMMF workers and involves the testing of the robots to assure a good performance during the week.

As Figure 19 shows the AMU is on during the whole shift consisting of ten hours. However, the cleaning and maintenance activities only last a maximum of 2 hours and 1 hour respectively, making a total of 3 hours. Under these circumstances unwanted extra consumption was detected, and improvements were proposed.

Finding a gap of seven hours in which the AMU is on but there is no activity being performed inside the booth, a reduction of six hours of its utilization was suggested. In order to prevent any contingency an extra hour was given to the activity time. Figure 20 represents the first improvement proposal.

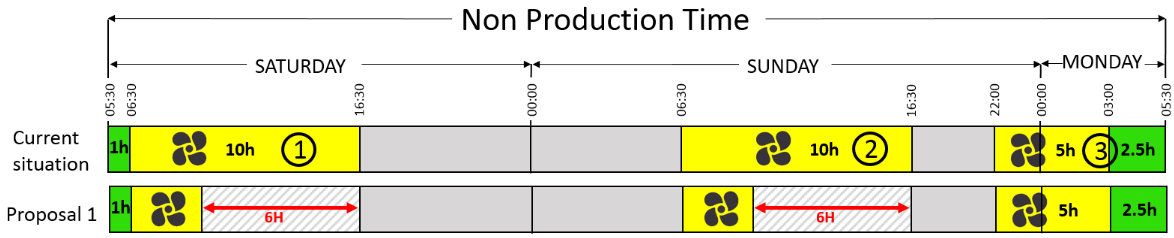


Figure 20. AMU's improvement proposal 1

Currently, the AMU uses a total of 648 MWh during the weekend shifts of a year. If a reduction of six hours is implemented possible savings are presented in Table 29.

	1		2		TOTAL
	Electricity	Natural Gas	Electricity	Natural Gas	
Reduction hours [h/week]	6	6	6	6	
Power [kW]	251.10	163	251	163	
Energy [MWh/week]	1.5	1.0	1.5	1.0	
Energy [MWh/yr]	72.3	46.9	72.3	46.9	
Energy Reduction [MWh/yr]	119		119		**238**
CO_2 Reduction [ton/yr]	11		11		**22**

Table 29. Potential savings AMU improvement 1.

To conclude the first part of the analysis, savings of 238MWh per year could be achieved.

When challenging period 3 energy utilization, it is important to take into account that the AMU has to reach optimal conditions at the end of this period as production starts right after. During this time frame trials are done in order to test all the equipment before production. So, this AMU's energy consumption has the only objective of conditioning the booths to perform trials and for production. Nevertheless, extra consumption was detected, and improvements were proposed.

Trials before production last 1.5 hours and after investigation it was found out that booth conditioning takes up to 1 hour. Needing only 2.5 hours out of the 7.5 hours used, an elimination of the saving mode was suggested. Figure 21 represents the second improvement proposal.

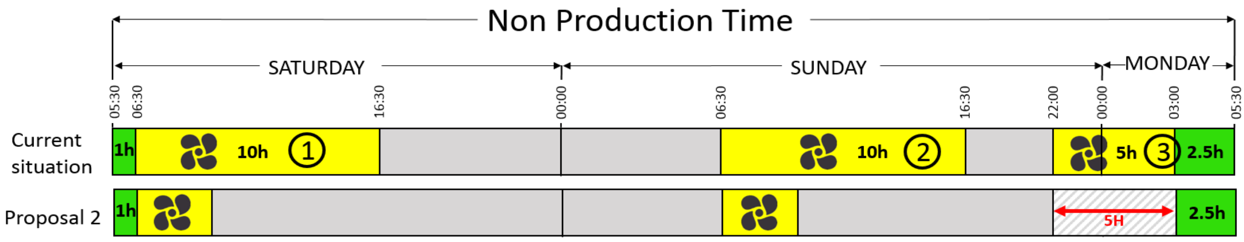


Figure 21. AMU's improvement proposal 2

The total energy use to condition the booth and for trials is 208 MWh per year. If an elimination of the saving mode is implemented possible savings are presented in Table 30.

	3	
	Electricity	Natural Gas
Reduction hours [h/week]	5	5
Power [kW]	251	163
Energy [MWh/week]	1.3	0.8
Energy [MWh/yr]	60.3	37.9
Energy Reduction [MWh/yr]	99	
CO_2 Reduction [ton/yr]	9	

Table 30. Potential savings AMU improvement 2.

Summing up the second part of the summary, a reduction of 99 MWh per year could be achieved.

Finally, if both improvements are implemented in the operational behaviour of the AMU, a total saving of 337 MWh per year in energy and of 31 Tons of CO_2 per year could be accomplished, see Table 31 . Figure 22 shows the total reduction that could be reached.

	Energy Reduction [MWh/year]	CO_2 Reduction [ton/year]
1	119	11
2	119	11
3	99	9
Total	**337**	**31**

Table 31. Total potential savings AMU

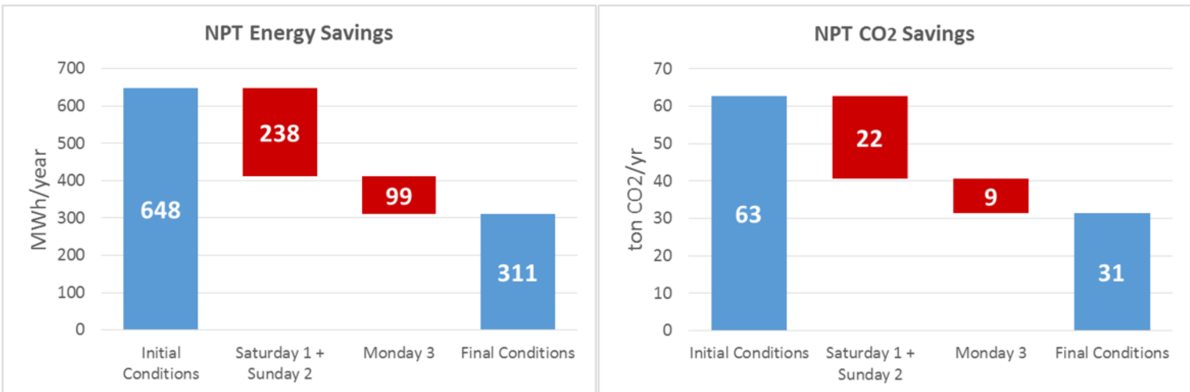


Figure 22. AMU's energy and CO_2 savings

In APPENDIX 5. Start Stop Report: AMU contains the report for the AMU's Start Stop analysis.

4.1.2 Sludge pumps

The primer sludge system is composed by three pumps. Figure 23 shows the sludge system for the primer.

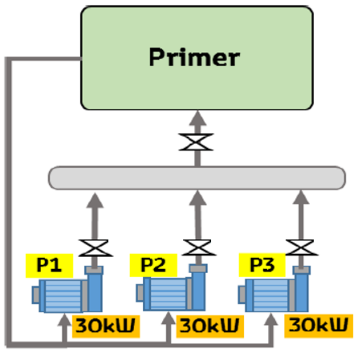


Figure 23. Primer's sludge system.

All three pumps work during production. However, when neither production or trials are being performed only one pump remains working. Figure 24 shows the working pattern of the sludge system.

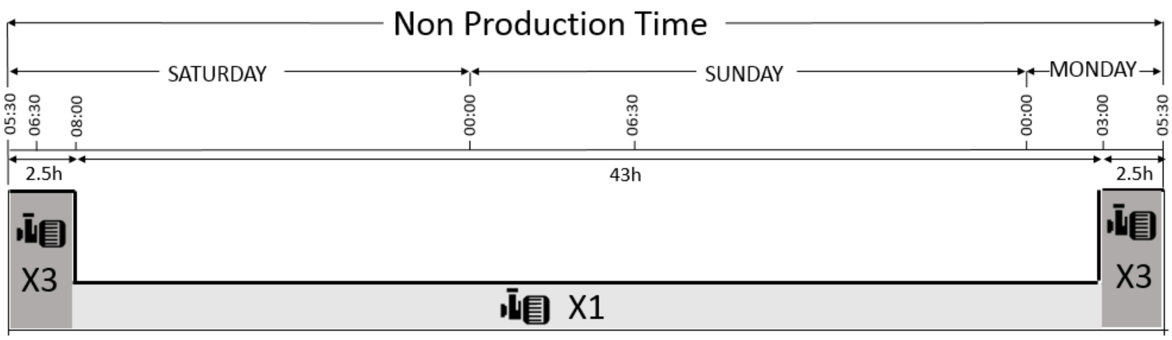


Figure 24. Sludge system pattern.

Primer booth is the only one with one pump working during NPT due to the structure of the booth. Because of how the beam that supports the robots was built there is a permanent paint dripping and in order to avoid any paint getting stuck, the sludge system is constantly running. Figure 25 helps to visualize the primer booth dripping problem.

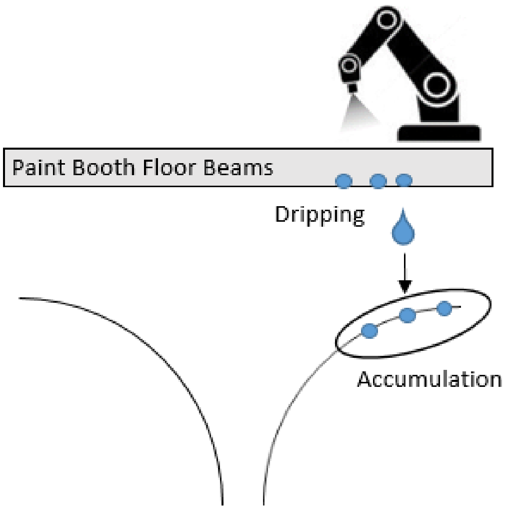


Figure 25. Primer booth dripping problem

Currently, the sludge system consumes a total of 61 MWh per year. Table 32 shows calculations performed.

	Primer	
Hours [h/week]	5	43
Number of pumps	3	1
Power per pump [kW]	22	22
Energy [MWh/week]	0.3	0.9
Energy [MWh/yr]	15.8	45.4
Energy Consumption [MWh/yr]	61	
CO_2 Consumption [ton/yr]	2.1	

Table 32. Primer's sludge system consumption.

Regarding all calculations made in this section, power data was obtained from APPENDIX 2. Data Energy Mapping. Energy consumption was computed using equation (5) and CO_2 emissions were calculated with factors presented in Table 25.

Even though paint dripping could cause many inconveniences, investigation was performed, and findings showed that it is not necessary to have a pump constantly running. Therefore, a reduction of the pump's working hours was suggested. In addition, a link between the operational pattern of the pumps and of the AMU was proposed. Figure 26 presents the improvement for the sludge system.

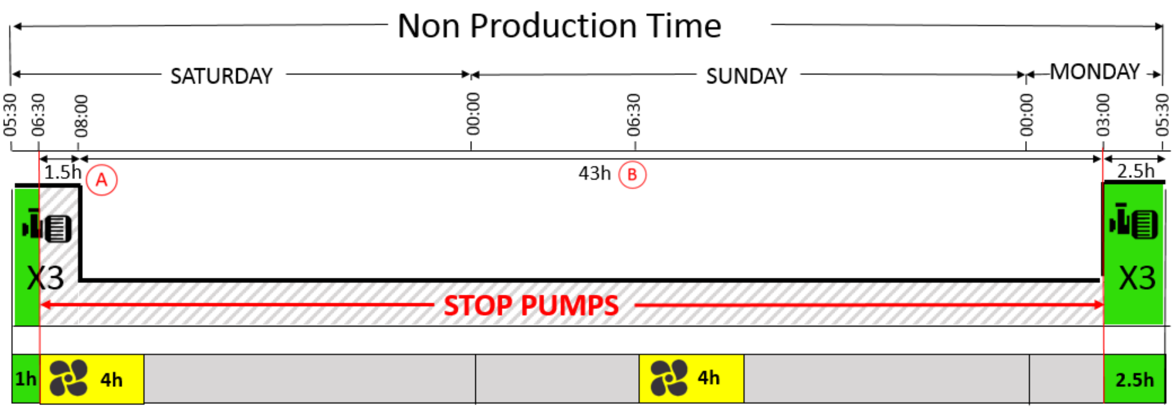


Figure 26. Sludge system improvement proposal.

As it is seen from Figure 26 pumps would only run when the AMU is operating in normal mode. This new operational behaviour would bring savings shown in Table 33.

	A	B	Total
Reduction hours [h/week]	1.5	43	
Number of pumps	3	1	
Power [kW]	22	22	
Energy [MWh/week]	0.10	0.9	
Energy [MWh/yr]	4.8	45.4	
Energy Reduction [MWh/yr]	5	45	50
CO_2 Reduction [ton/yr]	0.2	2	2.2

Table 33. Potential savings of sludge system improvement.

To conclude this study, up to 50 MWh per year could be saved, see Figure 27.

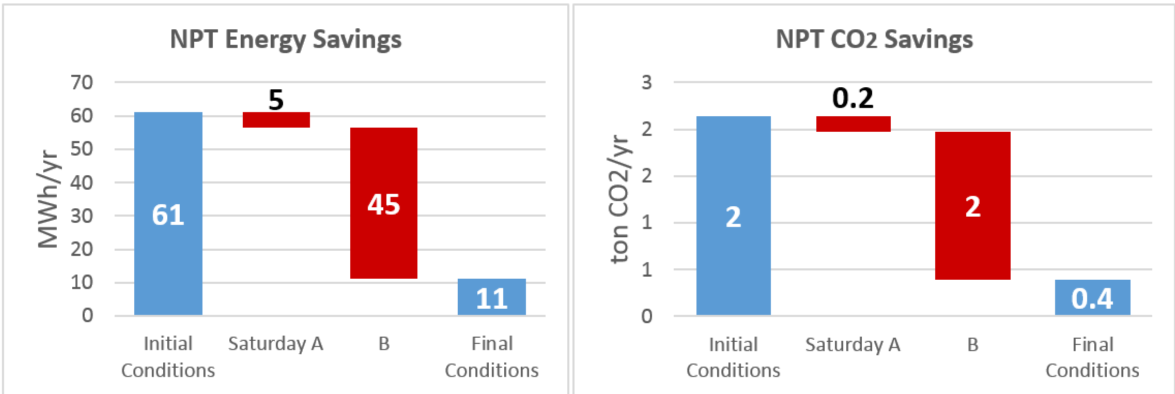


Figure 27. Pump's energy and CO_2 savings

APPENDIX 6. Start Stop Report: Sludge pumps contains a summary of sludge system Start Stop analysis.

4.2 Reduce

Challenge is one of the pillars that builds the Toyota Way. When improving energy efficiency, many directions could be taken. This section explains the ones that challenge equipment design criteria.

Within this category two improvements were suggested:

a. Optimize AMU's temperature and humidity set points.

b. Reduce booth air's speed

To ensure that the painting process meets all quality requirements, the AMU has to be constantly adjusting the humidity and temperature of the air that is coming from outside and going into the booths. Before, the required temperature and humidity was fixed and did not depend on outside conditions. However, studies were performed, and results showed that having a variable set point would bring savings without affecting the final result. In other words, the range of temperature and humidity required for the process would broaden and would stop being so tight, see Figure 28

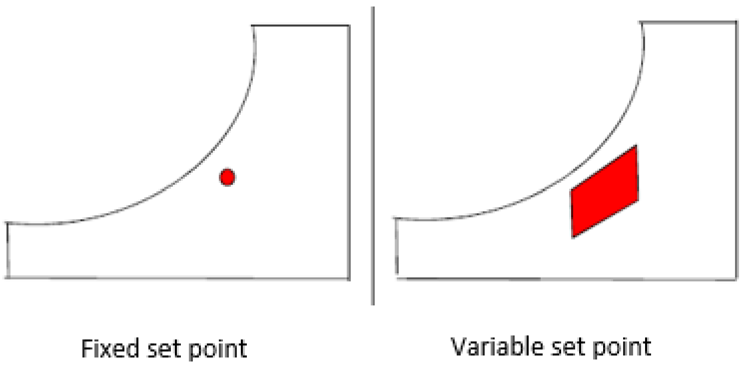


Figure 28. Set point improvement

Regarding the air's speed, it is also closely related with the paint's quality. Reducing the speed would mean lowering the supply fans' power and therefore saving energy, see Figure 29.

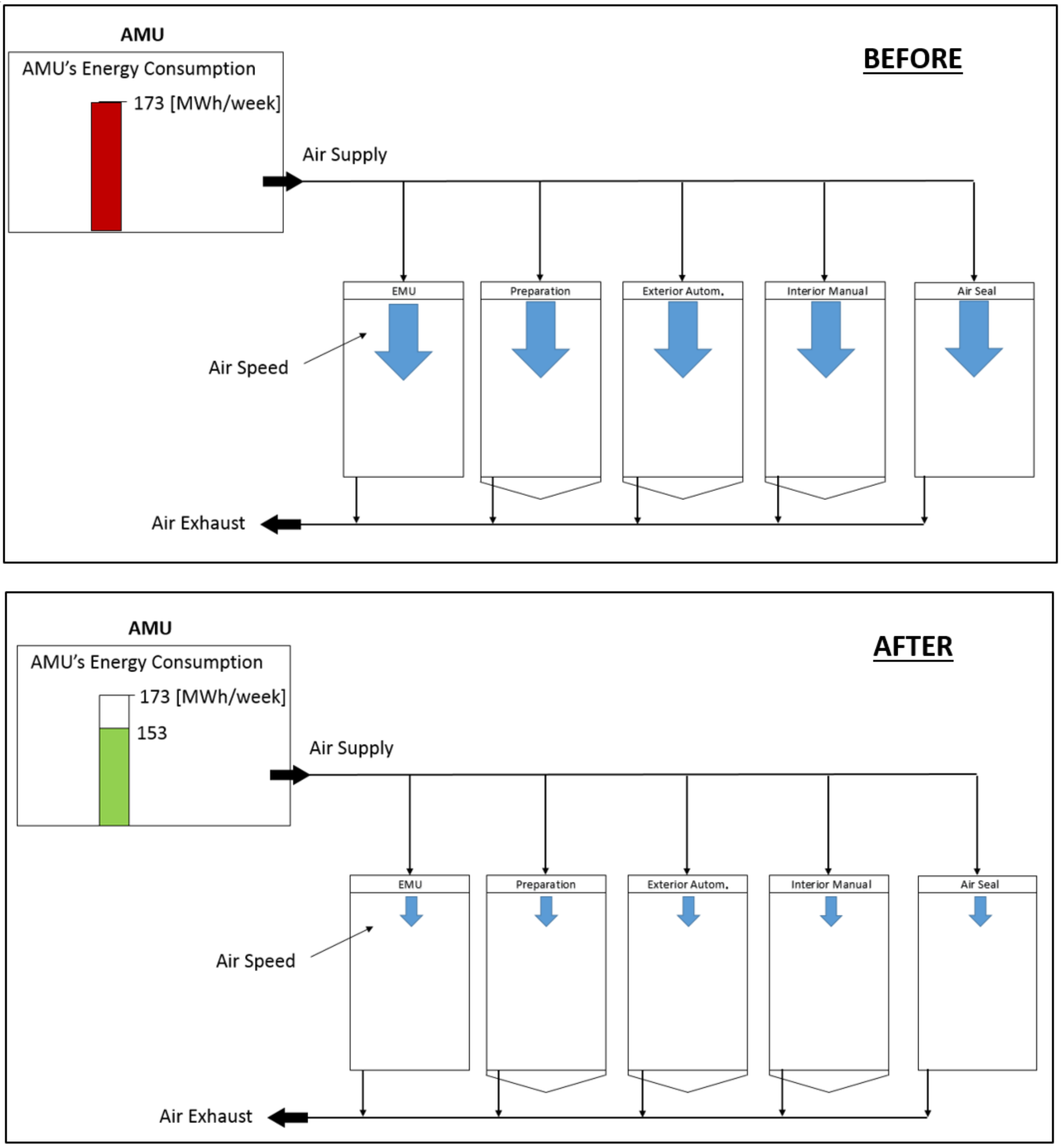


Figure 29. Air's speed improvement.

Results for both improvements are presented in Table 34.

	Energy savings [MWH/year]	CO_2 savings [tonCO_2/year]
Optimize temperature and humidity set points.	759	133
Reduce 5% booth's air speed	451	23

Table 34. Potential savings for reduce category

Data for these improvements will not be presented, only results as they are part of other study and not of this current thesis. However, as they are applicable to the primer booth they affect the final conclusion.

APPENDIX 7. Reduce report: Optimize temperature and humidity set points. and APPENDIX 8. Reduce report: Reduce booth air speed contain reports for both proposals.

4.3 Change

Once all operational improvements have been implemented, the only way to improve efficiency is by changing the equipment for a more efficient one. Therefore, this section will analyse the savings that could be achieved from switching incandescent lighting to LED and from improving the supply and exhaust fans' efficiency.

One way to reduce energy consumption is simply by changing from incandescent lighting to LED. Previous studies carried out in other Toyota's plants showed that a 50% energy reduction could be achieved. Calculations are shown below in Table 35.

Type lamp	Power per fixture [W]	Number of fixtures	Total Power [kW]	Hours per week	Weeks per year	Hours per year	Energy [MWh/year]	CO_2 consumption [tonCO_2/year]
Fluorescent	60	187	11.22	168	48	8064	90	3.2
LED	31	187	5.75	168	48	8064	46	1.6

Table 35. Lighting calculation

The total power and the energy and CO_2 consumption were calculated using equation (2), (5) and factors from Table 25 respectively.

LEDs could save around 44 MWh/year and 1.6 tonCO_2/year, see Figure 30.

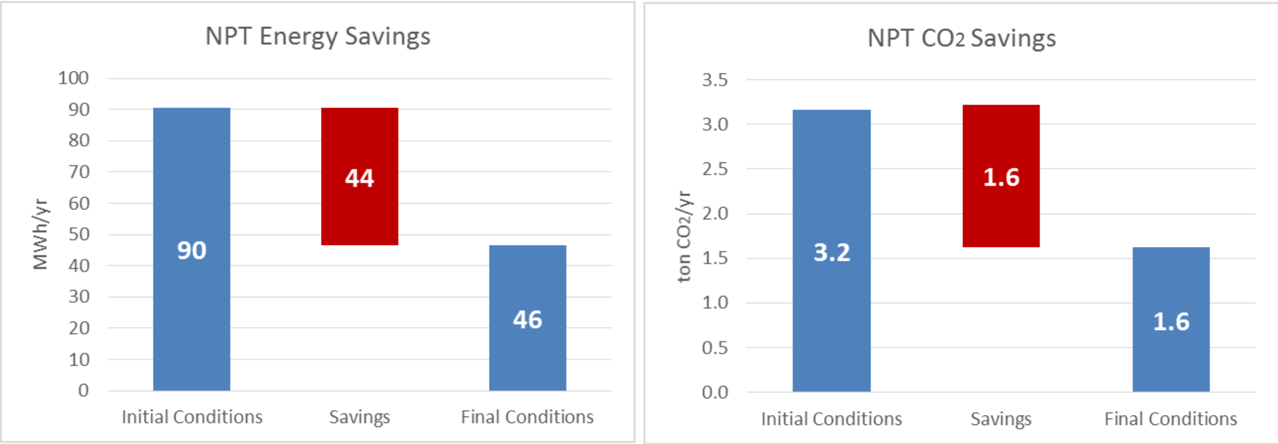


Figure 30. LED energy and CO_2 savings

APPENDIX 9. Change Report: LED Improvement contains the report for this improvement.

Other way to improve energy consumption is by using the most efficient technology available. APPENDIX 4. Primer Booth's Sankey Diagram shows a Sankey diagram of the energy consumption of the primer booth. As it can be seen in the diagram the equipment with the largest losses are the supply and exhaust fans. Hence, their replacement will be study.

When improving efficiency in the exhaust fans, electricity is saved. Higher efficiency means lower losses. Therefore, less consumption. Figure 31 gives a visual explanation of the reduction of losses when increasing efficiency.

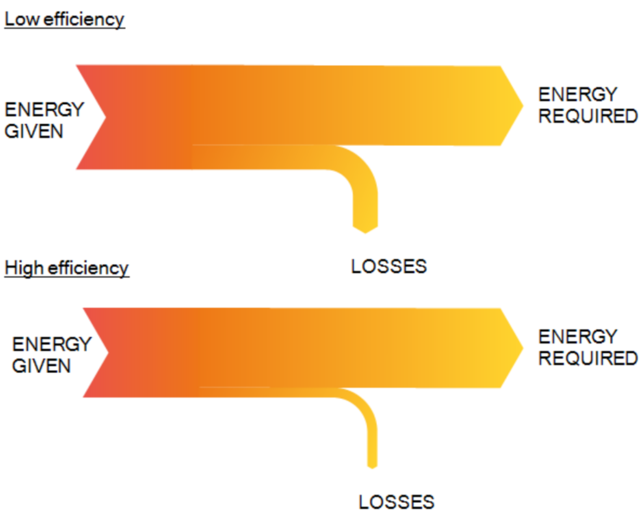


Figure 31. Exhaust fan efficiency

When improving efficiency in supply fans, electricity is saved but natural gas is increased. Because the supply fans are inside the air stream, their losses are recovered and used to heat, as shown in Figure 32.

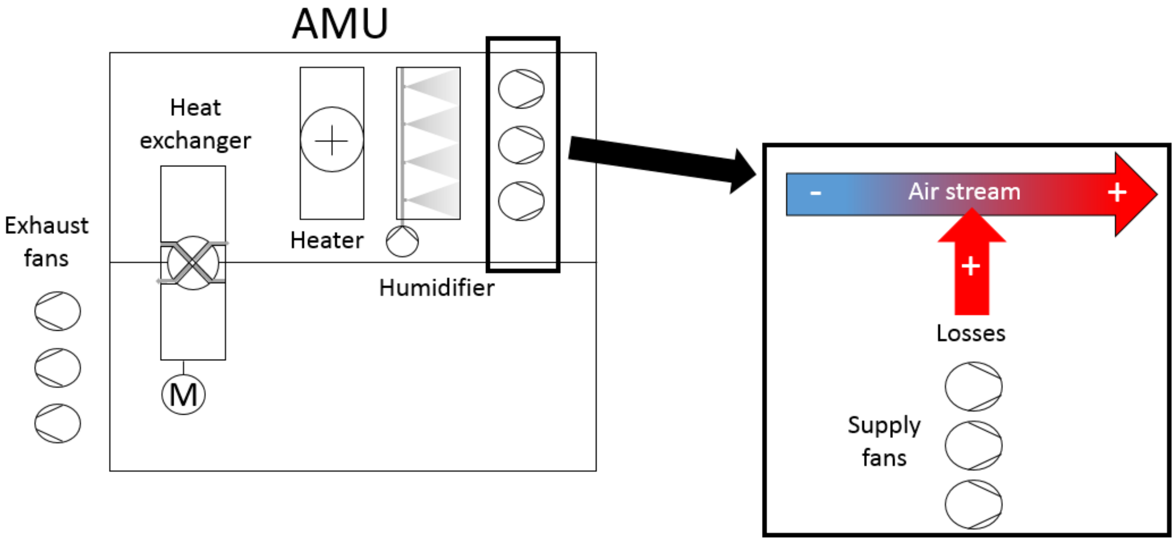


Figure 32. Supply fans' detail

Increasing the supply fans' efficiency would decrease their losses and more natural gas for the heater would be needed. Even though natural gas is cheaper than electricity, it emits more.

Now, a case study will be presented in which these assumptions are confirmed.

As data for supply fan is available, it will be used as input in the analysis, see Table 36.

Supply fan		
Flow	275,080	m^3/h
Power per fan	32	kW
Efficiency	52%	

Table 36. Input data supply fan analysis.

Using the efficiency factor, power lost in a supply fan is calculated as follows:

$$P_{lost}[kW] = \text{Power used } [kW] \cdot (1 - \text{Efficiency}) \tag{6}$$

$$P_{lost} = 32 \cdot (1 - 0.52) = 15.36 \text{ kW}$$

From calculations above, the total power used by the three fans to heat the air flow is 46.08 kW. Using equation (7) it is calculated the degrees the air flow increases.

$$\Delta T = \frac{P[W]}{\dot{m}\left[\frac{kg}{s}\right] \cdot C_p \left[\frac{J}{kgK}\right]} \quad (7)$$

$$\Delta T = \frac{46.08[kW]}{275080\,\frac{m^3}{h} \cdot \frac{1h}{3600s} \cdot 1.2\,\frac{kg}{m^3} \cdot 1.005\left[\frac{kJ}{kgK}\right]} = 0.5$$

Supply fans' losses increase the air flow's temperature 0.5 ^{0}C.

In order to prove assumptions, calculations will be repeated with a 70% fan's efficiency. In this context fans would consume 28.8kW and they would heat the air stream's temperature 0.31^{0}C. Hence, the heater would have to provide the 0.19^{0}C missing to make a total of 0.5^{0}C. Calculations were done using equation (6) and (7).

Power needed by the heater to provide 0.19^{0}C to the air stream is calculated using equation (7) as shown below.

$$P = \dot{m} \cdot C_p \cdot \Delta T = 275080\,\frac{m^3}{h} \cdot \frac{1h}{3600s} \cdot 1.2\,\frac{kg}{m^3} \cdot 1.005\left[\frac{kJ}{kgK}\right] \cdot 0.19 = 17.28kW$$

Table 36 shows results obtained.

	Before		After	
	Power [kW]	Temperature [^{0}C]	Power [kW]	Temperature [^{0}C]
Electricity	46.08	0.5	28.8	0.31
Natural Gas	-	-	17.28	0.19

Table 37. Efficiency comparison

To finish the study, emissions and cost will be calculated using factors from Table 25. Table 38 shows the results.

$Emissions_{before}/Emissions_{after}$	0.38
$Cost_{before}/Cost_{after}$	1.22

Table 38. Efficiency study: cost and emissions

To conclude, as ratios calculated above show, the more efficient fans are, the more emissions increase. However, from the economical point of view, cost decreases. Therefore, as this thesis is part of the Toyota Environmental Challenge 2050 that tries to reach cero emissions, this improvement will not be proposed.

4.4 Implementation

Once all actions suggested to use energy more efficiently have been explained the next step would be to prioritize their implementation.

A summary of the results is presented in Table 39.

	Kaizen Idea	**Energy Reduction** [MWH/year]	**CO_2 Reduction** [tonCO_2/year]
1	Stop sludge pumps when the AMU is off or in SM	50	2.2
2	Start supply/exhaust fan after production	337	31
3	Optimize temperature and humidity set points.	759	133
4	Reduce 5% booth’s air speed	451	23
5	Convert to LED lighting at booth	44	1.6

Table 39. Improvements summary

Every process has a minimum energy consumption and CO_2 emission. This minimum would be reached when implementing all possible improvements. In this case, if all actions are considered, 1641 MWh and 191 tons CO_2 per year could be reached, see Figure 33 and Figure 34.

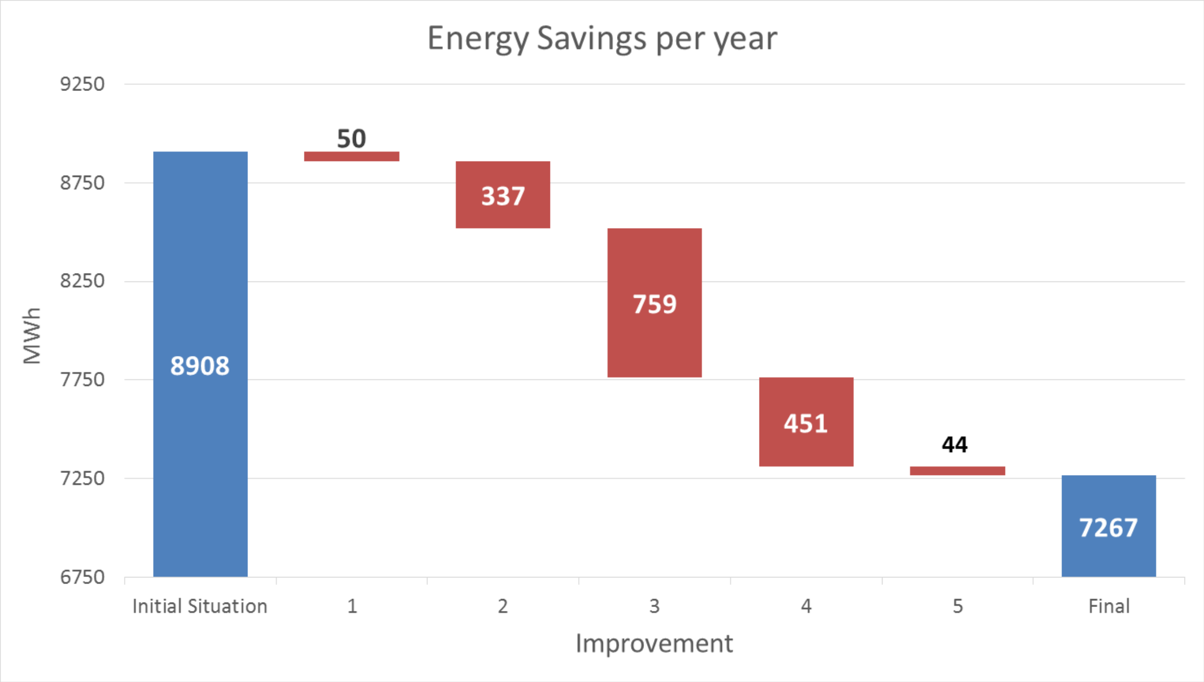


Figure 33. Energy Primer Booth

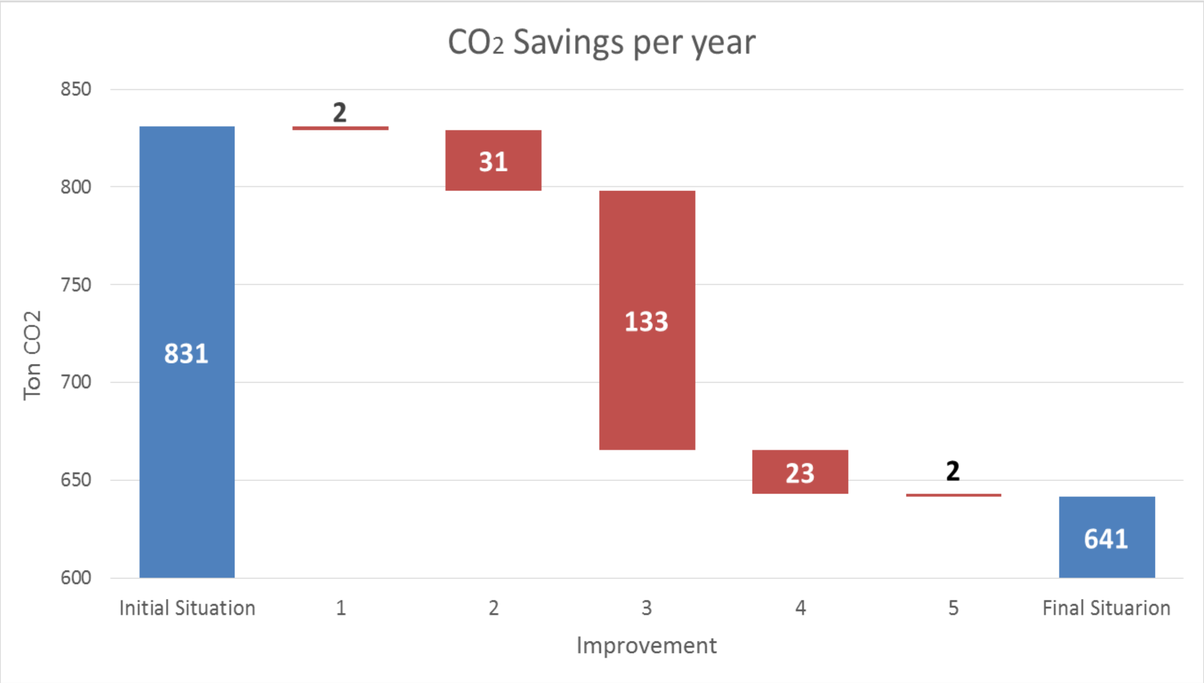


Figure 34. CO_2 Primer Booth

According to the Sankey diagram in APPENDIX 4. Primer Booth's Sankey Diagram the areas where reduction could have a large impact are the ones related with the AMU's equipment, see Figure 35.

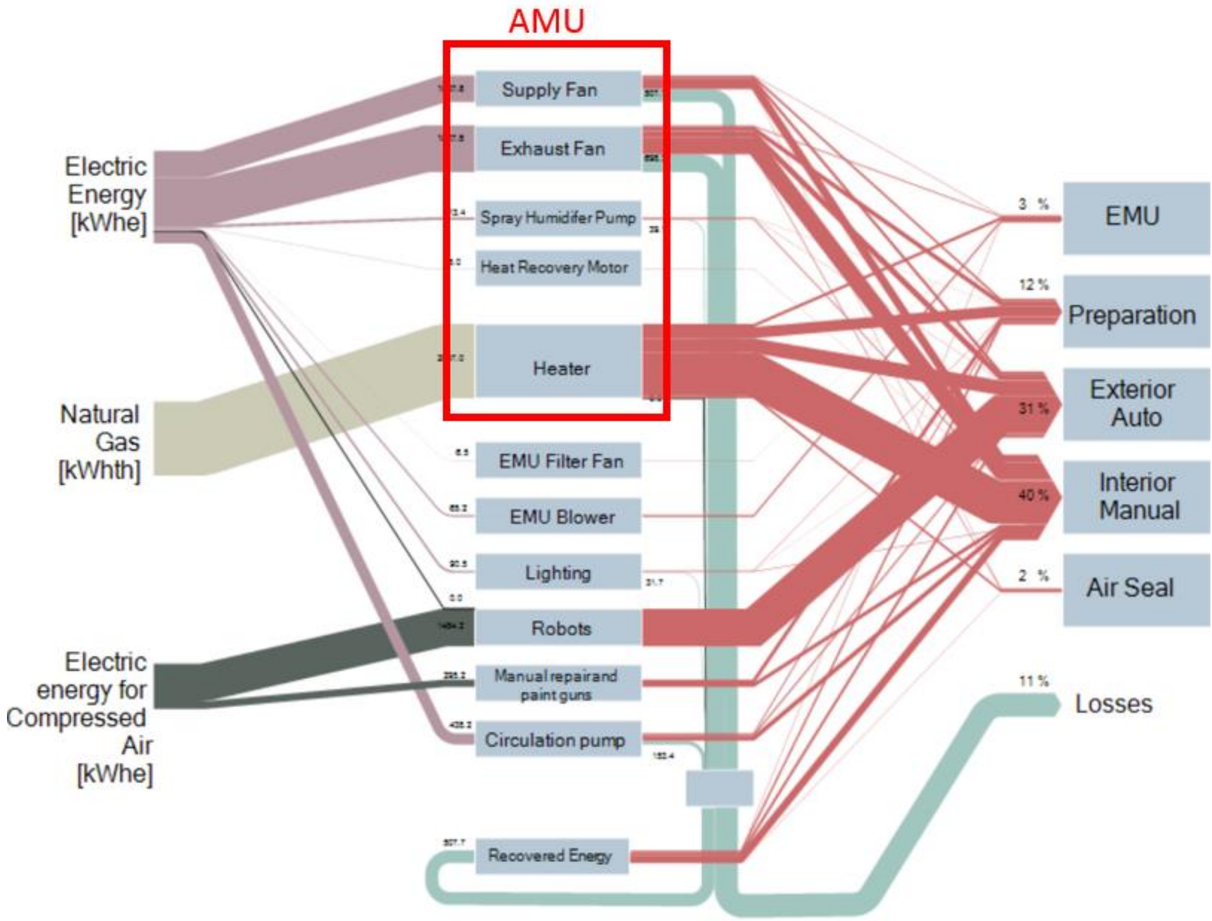


Figure 35. Sankey diagram Primer Booth.

Within the compiled list of improvements, lighting is the one with the least impact. In addition, it requires investment. Therefore, it will be left for the end.

Regarding the rest, the Start Stop of the AMU and sludge pump will go on top of the list because not only is there no investment required, but also, they have a great impact.

Then, as its implementation would mean both savings and collecting more information about the AMU, the implementation of optimize temperature and humidity set points is highly recommended. However, it requires big investment.

Finally, even though results of the air speed in the booth analysis are promising, it is needed further confirmation on the flows.

Table 40 contains the recommended order of implementation.

1	Start supply/exhaust fan after production
2	Stop sludge pumps when the AMU is off or in SM
3	Optimize temperature and humidity set points.
4	Reduce booth air speed
5	Convert to LED lighting at booth

Table 40. Implementation order

Chapter 5

Conclusion

Energy audit is a method used to understand how energy is consumed in order to reduce the unnecessary extra consumption that would lead to an efficient energy managing.

Due to the recent environmental consciousness, new energy policies and prices, companies are adopting a greener approach regarding their activities. Now, they pay more attention to their energy usage.

In this context, Toyota has challenged itself to reduce its CO_2 emissions by 2050. Therefore, this current thesis contributed to this challenge by analysing how the energy behaves in the primer booth and by suggesting improvements.

As a result of the thesis energy consumption of the primer booth was understood and a list of possible energy saving measures was generated. Therefore, the outcome went as expected and all proposed objectives of this thesis were achieved.

Focussing on the technical part, analysis showed that a large amount of energy could be saved just by changing the operational behaviour of the equipment. Further savings could also be achieved by changing the current technology into a more efficient one.

A total of 8908 MWh per year is what the primer booth is currently consuming. If implementing energy conservation measures a 17.9 % of the energy could be saved. Moreover, whether Energy Efficiency improvements were introduced, an additional of 0.5% would be saved over the original energy consumption. In addition, CO2 emissions could be reduced up to 190 tons of CO_2 per year from the initial 831 tons per year.

This analysis was performed in the TMMF paint shop. Hence, results could not be extrapolated to other plants. However, the methodology followed could be used when analysing other processes.

Finally, this study could be also useful when grasping the best available technology. As next steps, it would be interesting to perform the same analysis in other plants and study the differences, so the best possible procedure could be stablished for the primer booth.

Bibliography

[FYSI12] Fysikopoulos, A., D.Anagnostakis, K.Salonitis, G.Chryssolouris, "An Empirical Study of the Energy Consumption in Automotive Assembly", Procedia CIRP, vol. 3, pp. 477-482, 2012.

[EIA_17] Energy Information Administration (EIA), "International Energy Outlook 2017", pp. 5-17, September 2017.

[OUME16] Abduaziz Oumer, Samson Mekbib Atnaw, Jack Kie Cheng, Lakveer Singh, "Improving Energy Efficiency for the Vehicle Assembly Industry: A Discrete Event Simulation Approach", IOP Conference Series: Materials Science and Engineering, vol. 160, 2016.

[DUFL12] Duflou, Joost R., John W. Sutherland, David Dornfeld, Christoph Herrmannd Jack Jeswiet, Sami Kara, Michael Hauschild, Karel Kellens, "Towards energy and resource efficient manufacturing: A processes and systems approach", CIRP Annals, vol 61, pp. 587-609, 2012.

[SEOW11] Seow, Y., S. Rahimifard, "A framework for modelling energy consumption within manufacturing systems", CIRP Journal of Manufacturing Scinece and Technology, vol. 4, pp 258-264, 2011.

[TOYO__] Toyota, "Company Profile"

[TOYO15] Toyota, "Toyota's Environmental Initiatives 2015", 2015.

[FENG15] Feng, L., Laine Mears, "Analysis of HVAC Energy in Automotive Paint Shop", ASME 2015 International Manufacturing Science and Engineering Conference, vol. 2, Charlotte, 2015.

[AKAF16] Akafuah, Nelson K., Sadegh Poozesh, Ahmad Salaimeh, Gabriela Patrick, Kevin Lawler, Kozo Saito, "Evolution of the Automotive Body Coating Process—A Review", 2016.

[AESS02] AESSEAL, "A Guide to Seals in the Automotive Industry, Pre-Treatment & Paint Plants", Rotherham, 2002.

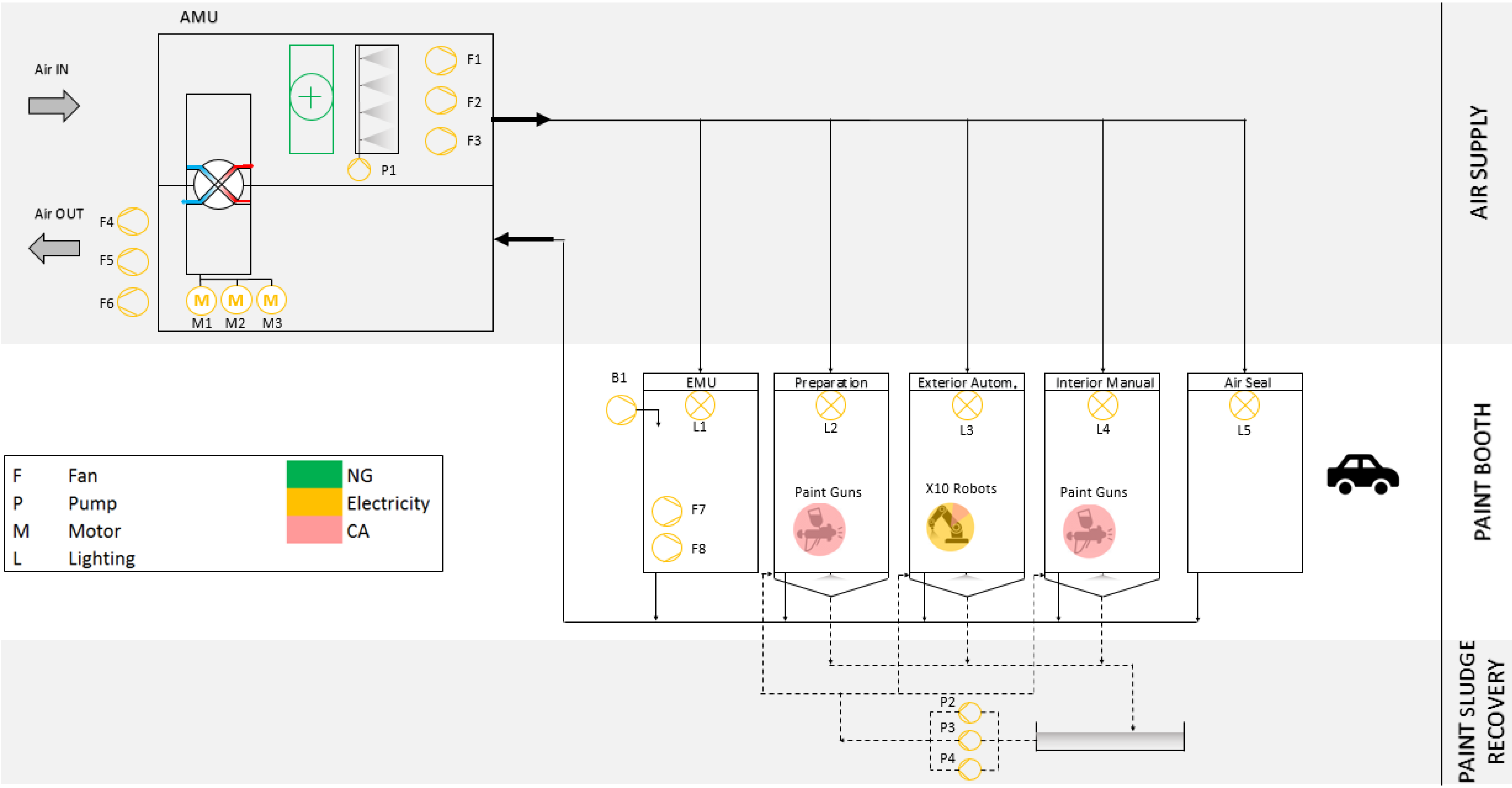
[ARTI13] Artid. Trakultongchai, Srisawat. Supsomboon, and Kamol. Limtanyakul, "Process Simulation and Improvement of Automotive Paint Shop", International Journal of Mining, Metallurgy & Mechanical Engineering, vol 1, pp. 2320-4060, 2013.

[FATH08] Fathil M., "Painting Process Improvement For Automotive Industry", Universiti Malaysia Pahang, 2008.

[GOLD07] Goldschmidt, Artur, Hans-Joachim Streitberger, "Basf Handbook On Basics of Coating Technology", vol 2, Germany, 2007.

[HOLE__] Holecek, John B., "Technical Requirements for Using Recirculation Paint Spray Booths", The Warren Group Inc.

APPENDIX 1. Primer Booth Process Flow

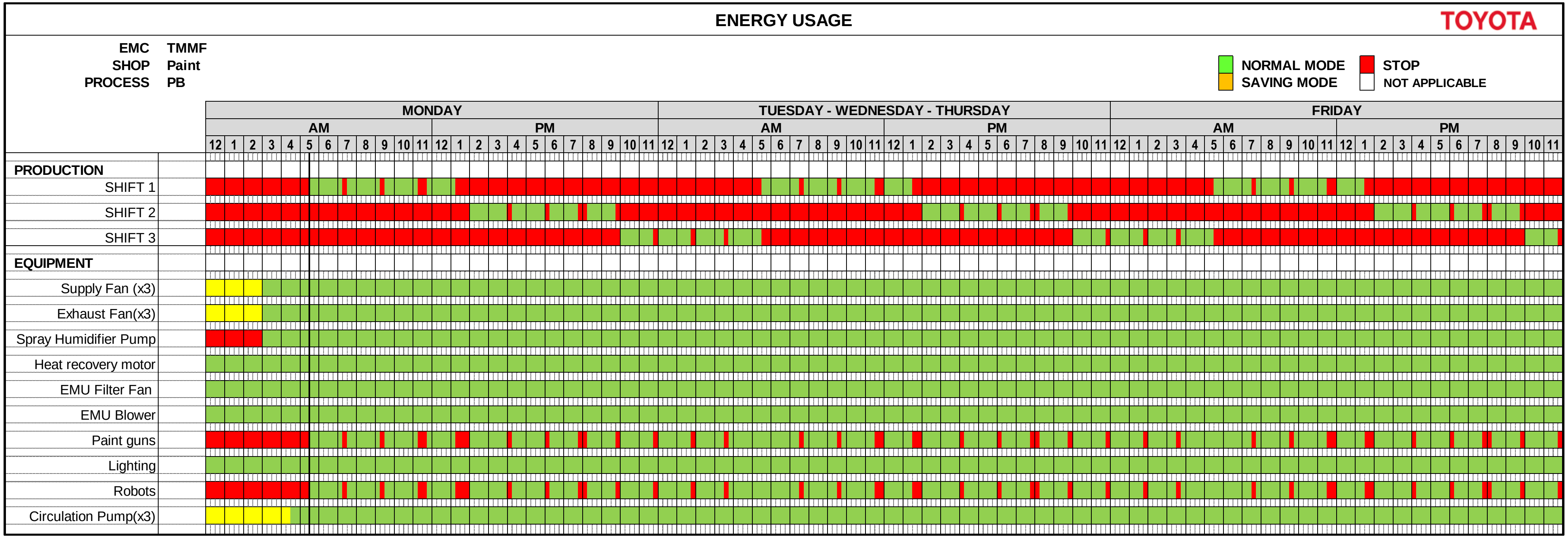


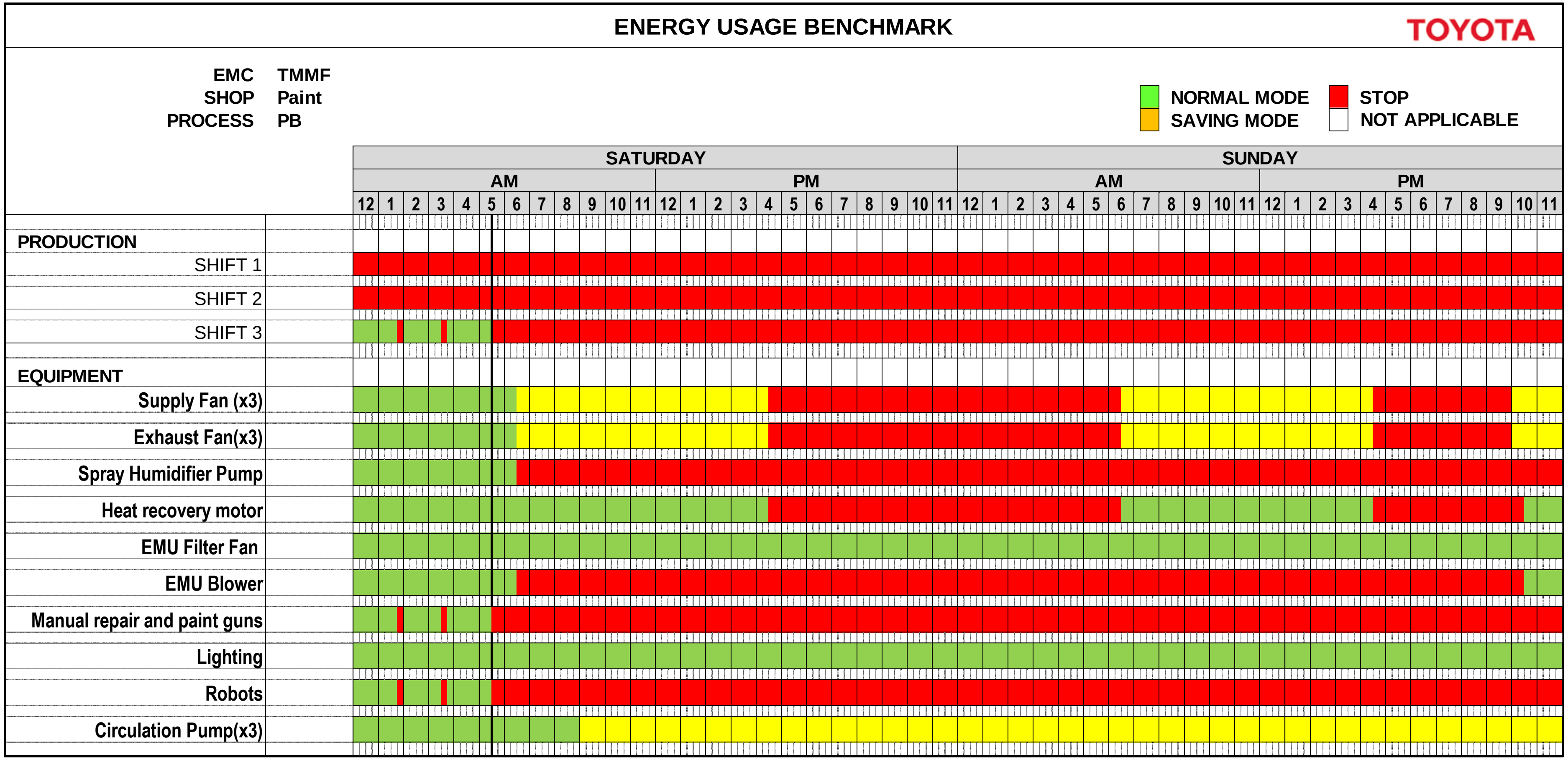
APPENDIX 2. Data Energy Mapping

					Installed Power				**Production time**		**Non- Production time**
	Equipment	Component	Number	Utility	Per equipment		Total		One fan [kW]	Total Average Power Demand [kW]	Total Average Power Demand [kW]
AHU		Supply Fan	3	E	90	[kWe]	270	[kWe]	53	159	62
AHU		Exhaust Fan	3	E	110	[kWe]	330	[kWe]	93	279	100
AHU		Spray Humidifier Pump	1	E	30	[kWe]	30	[kWe]	18	18	1
AHU		Heat Recovery Motor	3	E	1.5	[kWe]	4.5	[kWe]	0.7	2.1	1
AHU		Heat Recovery Cleaning Pump	1	E	4	[kWe]	4	[kWe]	0	0	0
AHU		Heater	1	NG	-	[kWth]	-	[kWth]	-	-	117
AHU		Anti-frost Heater Humidifier	3	E	2.5	[kWe]	7.5	[kWe]	0	0	0
Booth	EMU	Filter Fan	2	E	0.4	[kWe]	0.8	[kWe]	0.4	0.8	1
Booth	EMU	Air Handling Unit	1	E	11	[kWe]	11	[kWe]	11	11	2
Booth	Preparation	Manual repair guns	4	CA	-	L/min	520	L/min	-	27.62	0
Booth	Preparation	Lighting	70	E	0.06	[kWe]	4.2	[kWe]	0.06	4.2	4
Booth	Exterior Automatic	Robots guns	10	CA	-	L/min	5330	L/min	-	283.1	0
Booth	Exterior Automatic	Lighting	27	E	0.06	[kWe]	1.62	[kWe]	0.06	1.62	2
Booth	Interior Manual	Paint guns	-	CA	-	L/min	540	L/min	-	28.68	0
Booth	Interior Manual	Lighting	90	E	0.06	[kWe]	5.4	[kWe]	0.06	5.4	5
Paint Sludge		Circulation Pump	3	E	30	[kWe]	90	[kWe]	22	66	25

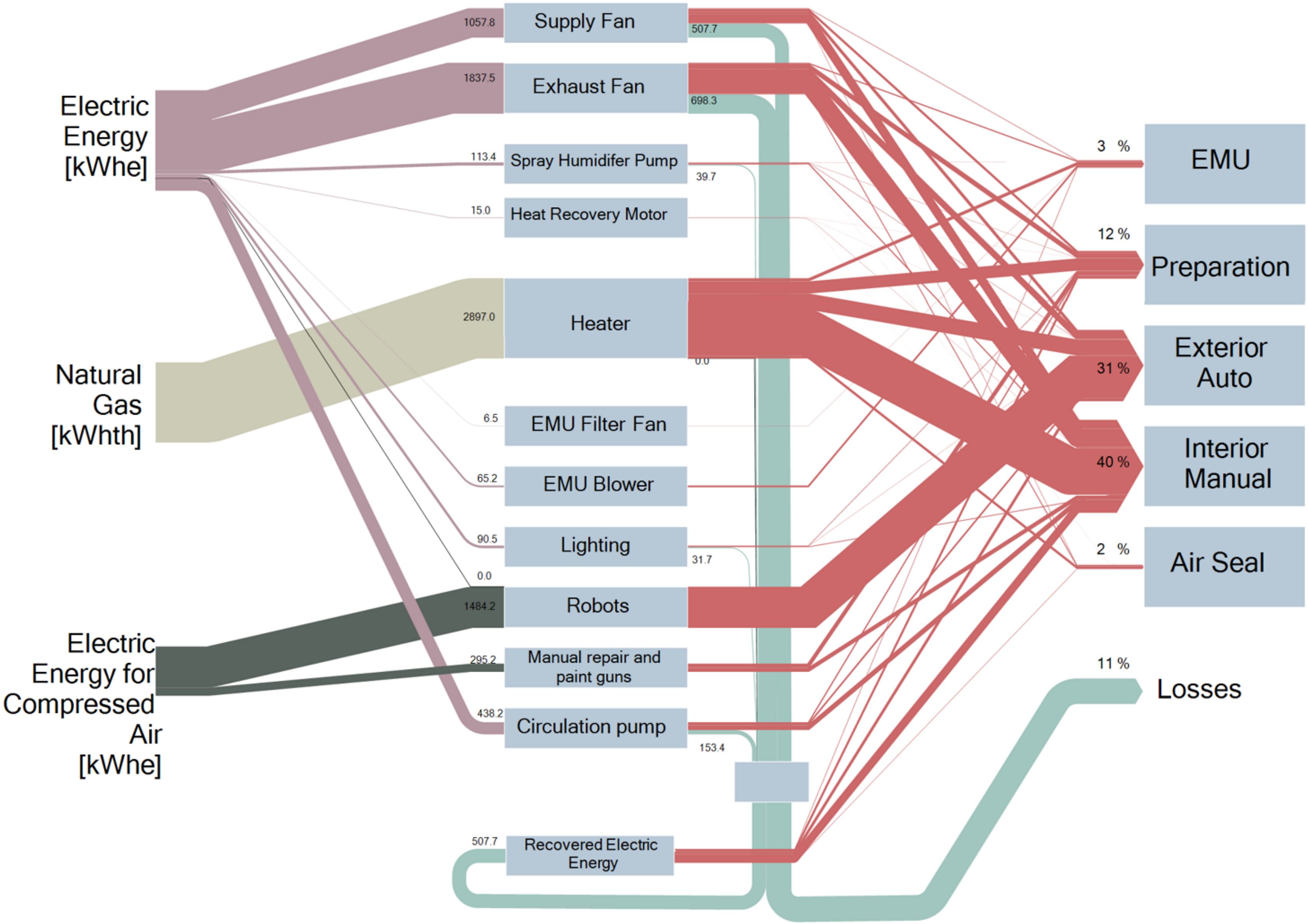
			Working hours Production Time		Working hours Non-production Time		Measured / Calculated Energy PT + NPT	CO_2 Emissions
	Equipment	Component	[h/week]	[h/year]	[h/week]	[h/year]	[MWh/year]	[Ton CO_2/year]
AMU		Supply Fan	120	5760	48	2304	1058	37
AMU		Exhaust Fan	120	5760	48	2304	1838	64
AMU		Spray Humidifier Pump	120	5760	48	2304	106	4
AMU		Heat Recovery Motor	120	5760	48	2304	15	1
AMU		Heat Recovery Cleaning Pump	0	0	48	2304	0	-
AMU		Heater	120	5760	48	2304	3509	642
AMU		Anti-frost Heater Humidifier	0	0	48	2304	0	-
Booth	EMU	Filter Fan	120	5760	48	2304	6	0
Booth	EMU	Air Handling Unit	120	5760	48	2304	68	2
Booth	Preparation	Manual repair guns	109.25	5244	48	2304	145	5
Booth	Preparation	Lighting	120	5760	48	2304	34	1
Booth	Exterior Automatic	Robots guns	109.25	5244	48	2304	1485	52
Booth	Exterior Automatic	Lighting	120	5760	48	2304	13	0
Booth	Interior Manual	Paint guns	109.25	5244	48	2304	150	5
Booth	Interior Manual	Lighting	120	5760	48	2304	44	2
Paint Sludge		Circulation Pump	120	5760	48	2304	438	15

APPENDIX 3. Start Stop Pattern




ENERGY USAGE BENCHMARK
TOYOTA
EMC TMMF
SHOP Paint
PROCESS PB
NORMAL MODE
SAVING MODE
STOP
NOT APPLICABLE
SATURDAY
SUNDAY
AM
PM
AM
PM
12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11
PRODUCTION
SHIFT 1
SHIFT 2
SHIFT 3
EQUIPMENT
Supply Fan (x3)
Exhaust Fan(x3)
Spray Humidifier Pump
Heat recovery motor
EMU Filter Fan
EMU Blower
Manual repair and paint guns
Lighting
Robots
Circulation Pump(x3)

APPENDIX 4. Primer Booth’s Sankey Diagram

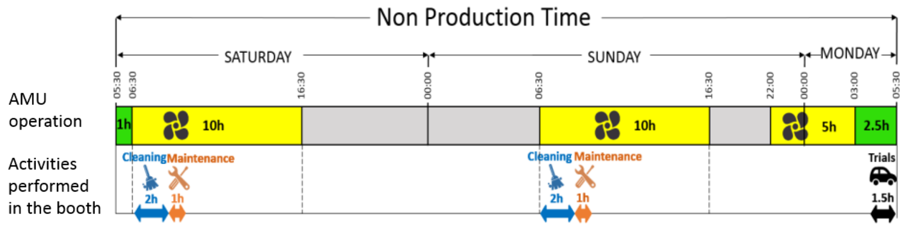


APPENDIX 5. Start Stop Report: AMU

TOYOTA	ENERGY KAIZEN REPORT	Date	25/04/2018	Initiator	C. Canbay / M. Dekeyser / C.Jimenez
Title	OPTIMIZATION OF PAINT BOOTH AIR MAKE UP UNIT'S(AMU) OPERATION DURING NON PRODUCTION TIME(NPT)				

EMC (issuing kaizen)	Shop	Process	Utility	Improvement Category
TMMF	Paint	Booth	Electricity	[X] Operational / Maintenance improvement; [ ] Equipment / Process improvement

BEFORE



PROBLEMS

1.AMU works at all time during weekend shift but only required for 3h. Activities performed during weekend shift: Cleaning: 2h and Maintenance: 1h

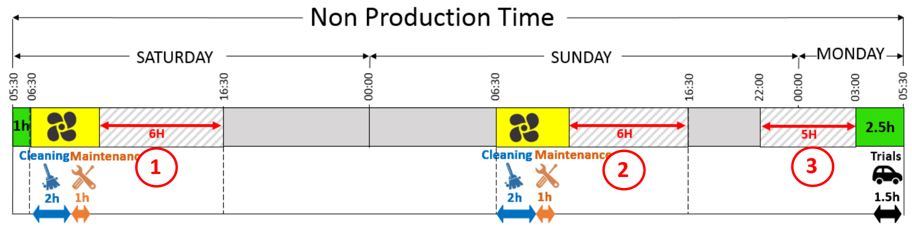
2.AMU operates manually

3.Monday morning AMU starts much earlier than requiered. Only needed in normal mode to run trials before production.

LEGEND

	Supply & Exhaust Fan	Gas Burner	Spray Humidifier
Normal Mode	Run at NORMAL speed	Control Temp. [19-26] ºC	RUN
Energy Saving Mode	Run at REDUCED speed	Control Temp. 18ºC	STOP
Stop Mode	STOP	STOP	STOP

AFTER

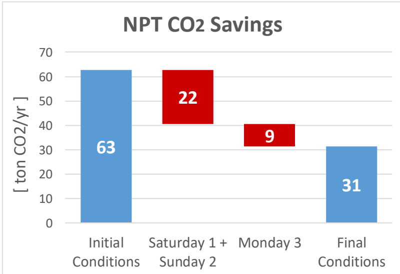


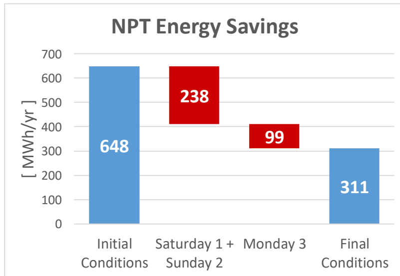
COUNTERMEASURES

1.Adjust operation time with activities plus one hour for contigency, 4h new total running time. Activities match with AMU operation time

2.Automatic Start/Stop of the AMU based on confirmation from cleaning

3.Eliminate monday morning energy saving mode. Early start stopped becasue is not needed, but still keep 1h of early start of normal mode before trials.





CALCULATION SHEET

ESTIMATIONS

Investment [Eur]		Energy Reduction [MWh/yr]	CO2 Reduction [ton/yr]	Cost Reduction [k€/yr]	Cost Reduction/veh [€/veh]	Simple PBT [yr]
Equipment	-	337	31	-	-	-
Manpower	-				Production Vol. [veh/yr] 234040	
Total						

Post Implementation Verification

Investment [Eur]		Energy Reduction [MWh/yr]	CO2 Reduction [ton/yr]	Cost Reduction [k€/yr]	Cost Reduction/veh [€/veh]	Simple PBT [yr]
Equipment						
Manpower						
Total					Production Vol. [veh/yr]	

Yokoten possible?

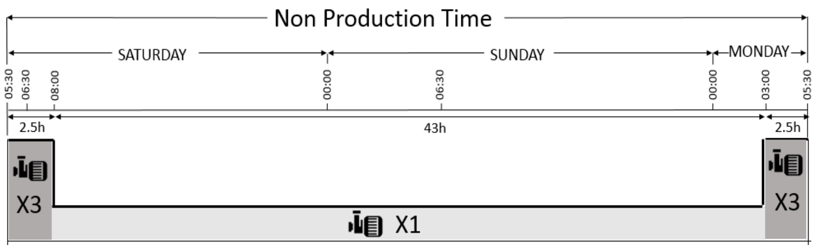
- [ ] Impossible
- [X] Same Process
- [ ] Other process

APPENDIX 6. Start Stop Report: Sludge pumps

TOYOTA	ENERGY KAIZEN REPORT	Date	25/04/2018	Initiator	C. Canbay / M. Dekeyser / C.Jimenez
Title	OPTIMIZATION OF PAINT BOOTH SLUDGE PUMPS OPERATION DURING NON PRODUCTION TIME(NPT)				

EMC (issuing kaizen)	Shop	Process	Utility	Improvement Category
TMMF	Paint	Booth	Electricity	[X] Operational / Maintenance improvement [ ] Equipment / Process improvement

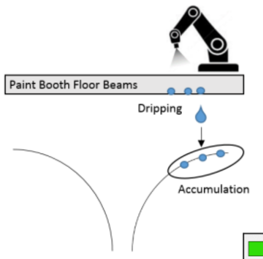
BEFORE



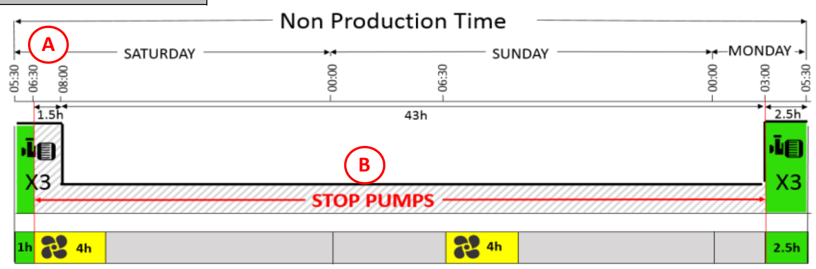
PROBLEMS

1. Sludge system continues working 2.5h after production has finished.

2.Primer's sludge system partly working during whole weekend due to paint dripping from robot's beam.



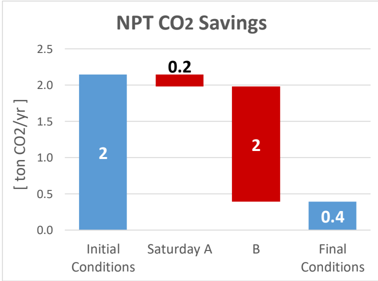
AFTER

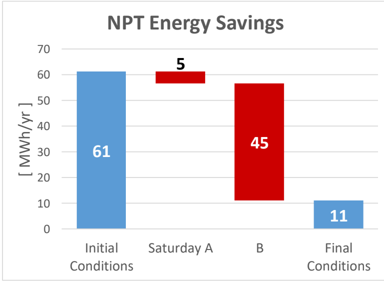


COUNTERMEASURES

1. Interlock sludge system operation with AMU's operation pattern.Pumps only run when AMU's normal mode is ON. Stop pumps when AMU is on saving mode or when there is no production.

2. No need to run one pump the whole weekend for the Primer Booth. Enough with the 2.5h before production to avoid paint getting sticked.





LEGEND

	Supply & Exhaust Fan	Gas Burner	Spray Humidifier
Normal Mode	Run at NORMAL speed	Control Temp. [19-26] ºC	RUN
Energy Saving Mode	Run at REDUCED speed	Control Temp. 18ºC	STOP
Stop Mode	STOP	STOP	STOP

CALCULATION SHEET

ESTIMATIONS

Investment [Eur]		Energy Reduction [MWh/yr]	CO2 Reduction [ton/yr]	Cost Reduction [k€/yr]	Cost Reduction/veh [€/veh]	Simple PBT [yr]	Yokoten possible?
Equipment	-	50	2.2	-	-	-	[ ] Impossible
Manpower	-				Production Vol. [veh/yr] 234040		[X] Same Process
Total							[ ] Other process

Post Implementation Verification

Equipment						
Manpower						
Total					Production Vol. [veh/yr]	

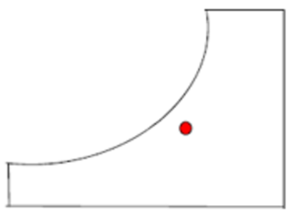
APPENDIX 7. Reduce report: Optimize temperature and humidity set points.

TOYOTA	ENERGY KAIZEN REPORT	Date	-	Initiator	-
Title	OPTIMIZATION OF AMU'S HUMIDITY AND TEMPERATURE SET POINTS				

EMC (issuing kaizen)	Shop	Process	Utility	Improvement Category	
TMMF	Paint	Air Supply	Electricity	[X] Operational / Maintenance improvement	[ ] Equipment / Process improvement

BEFORE

FIXED SET POINT



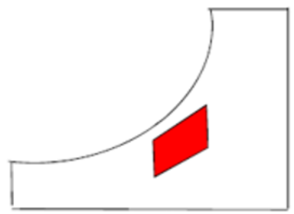
PROBLEMS

A lot of energy is consumed to adjust outside air for the painting process.

Quality requirements are not needed to be so tight.

AFTER

VARIABLE SET POINT



COUNTERMEASURES

Outside air's humidity and temperature are adjusted according to its initial conditions.

Energy was reduced by iexpanding the booth temperature and humidity operating window.

CALCULATION SHEET

ESTIMATIONS

Investment [Eur]		Savings: Energy Reduction [MWh/yr]	Savings: CO2 Reduction [ton/yr]	Savings: Cost Reduction [k€/yr]	Savings: Cost Reduction/veh [€/veh]	Simple PBT [yr]
Equipment						
Manpower						
Total		759	133	-	- Production Vol. [veh/yr] 234040	
Post Implementation Verification						
Equipment						
Manpower						
Total					Production Vol. [veh/yr]	

Yokoten possible?

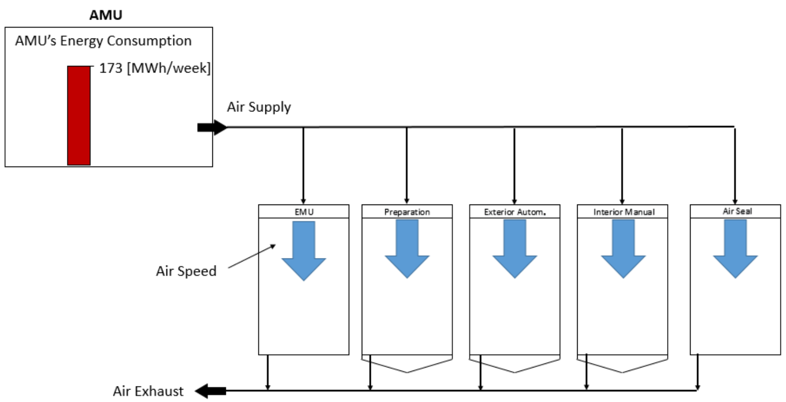
- [ ] Impossible
- [X] Same Process
- [ ] Other process

APPENDIX 8. Reduce report: Reduce booth air speed

TOYOTA	ENERGY KAIZEN REPORT	Date	-	Initiator	-
Title	REDUCE AIR SPEED IN THE BOOTHS				

EMC (issuing kaizen)	Shop	Process	Utility	Improvement Category
TMMF	Paint	Air Supply	Industrial Water	[X] Operational / Maintenance improvement [ ] Equipment / Process improvement

BEFORE

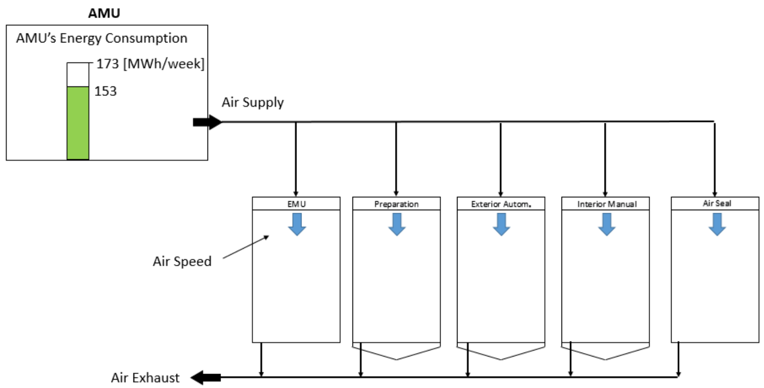


PROBLEMS

Air speed above requirements

AMU working more than needed.

AFTER



COUNTERMEASURES

Air speed in the booths reduced

AMU consuming less. Fans use less power

CALCULATION SHEET

ESTIMATIONS

Investment [Eur]		Savings					Yokoten possible?
		Energy Reduction [MWh/yr]	CO2 Reduction [ton/yr]	Cost Reduction [k€/yr]	Cost Reduction/veh [€/veh]	Simple PBT [yr]	[ ] Impossible
Equipment	-	976	138.0	-	-	-	[X] Same Process
Manpower	-				Production Vol. [veh/yr] 234040		[ ] Other process
Total							

Post Implementation Verification

Equipment						
Manpower						
Total					Production Vol. [veh/yr]	

APPENDIX 9. Change Report: LED Improvement

TOYOTA	ENERGY KAIZEN REPORT	Date	-	Initiator	-
Title	ENERGY SAVING BY SWITCHING FLUORESCENT TO LED				

EMC (issuing kaizen)	Shop	Process	Utility	Improvement Category
TMMF	Paint	Lighting	Electricity	☐ Operational / Maintenance improvement ☒ Equipment / Process improvement

BEFORE

Current lighting used in TMMF

60W

▼ **EFFICIENCY**

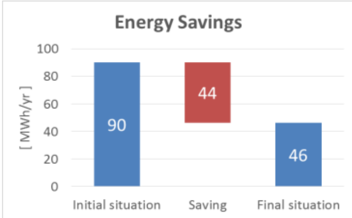
PROBLEMS

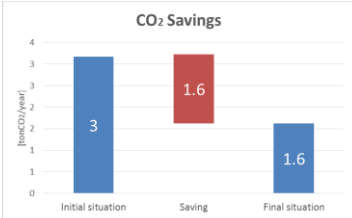
Fluorescent lighitng very inefficient

AFTER

COUNTERMEASURES

Change fluorescent for LED





LED lighting proposal

31W

▲ **EFFICIENCY**

CALCULATION SHEET

ESTIMATIONS

Investment [Eur]		Energy Reduction [MWh/yr]	CO2 Reduction [ton/yr]	Cost Reduction [k€/yr]	Cost Reduction/veh [€/veh]		Simple PBT [yr]
Equipment		44	1.6	-	-		
Manpower							
Total					Production Vol. [veh/yr]	234040	
Post Implementation Verification							
Equipment							
Manpower							
Total					Production Vol. [veh/yr]		

Yokoten possible?

- ☐ Impossible
- ☒ Same Process
- ☐ Other process