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Bachelor's Thesis

Study and enhancement of R-packages for DOE in laser material processing.

under the supervision of

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Abstract

This thesis approaches the statistical and engineering world through applying the Design Of Experiments to Laser Technology. For laser cutting and welding, the most important parameters are studied and incorporated into Full and Fractional Factorial experiments. For creating a repeatable method, the DOE is applied through the R language, coding a shiny app. At the end, an app is presented. It applies the mentioned DOE methods to a selection of laser parameters, showing which are the most influential of the process and the relations between them.

Kurzfassung

Diese Dissertation nähert sich der Statistik- und Ingenieurswelt durch die Anwendung des Versuchsdesigns auf die Lasertechnik. Beim Laserschneiden und Schweißen werden die wichtigsten Parameter untersucht und in Full- und Fractional-Factorial-Experimente integriert. Um eine wiederholbare Methode zu erstellen, wird das DOE über die R-Sprache angewendet und eine shiny app codiert. Am Ende wird eine App präsentiert. Es wendet die genannten DOE-Methoden auf eine Auswahl von Laserparametern an, die zeigen, welche die einflussreichsten des Prozesses sind und welche Beziehungen zwischen ihnen bestehen.

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Objectives

This document is written with the purpose of studying the Design Of Experiments and applying it to laser material technology via a statistical programme called R. The plan of this study is to approach the statistical world to the laser engineering for finding a time- and cost-effective way to test experiments.

The scope of the study is to create an interactive web app to facilitate the Design Of Experiments applied to laser. For the creation of this app, a deep study on laser technology, design of experiments and app development must be done. Nevertheless, this application will cover only a basic aspect on the design of experiments and it will be left for a further improvement.

1. Introduction

Only 60 years ago since the first laser presentation in the scientific world. However, the progress in investigation and development made it enter fully into our daily lives. Nowadays the laser technology has an almost endless range of possibilities. Cutting, drilling, welding, and heat-treating is mainly laser made in the industry.

The laser (acronym for: Light Amplification by the Stimulated Emission of Radiation) is a device that transforms energy into light through a process of optical amplification. The principal qualities of the laser radiation are to theoretically be: (1) *parallel waves*, emitted as a narrow beam in a concrete direction, (2) *monochromatic*, as long as lasers only emit a certain wavelength (color), and (3) *coherent*, being in phase in time and space, meaning it can be superpositioned.

These characteristics allow lasers to be extremely precise, powerful and able to travel vast distances. Moreover, the range of power and size of laser commercialization became noticeably ample, creating an ideal environment for its extension [1].

As laser technology is such a wide ambit, in this document it will be narrowed for laser material processing. Specifically, laser cutting and welding, which are the most widespread tasks. Some images of laser cutting and welding are attached for a visual concept of the process.

The **Figure 1** is an example of laser welding where two curved metal sheets are joint. The image is taken from *The Fabricator magazine*, which is a north American magazine of fabricating industry. The **Figure 2** is an example of laser cutting coming from the ACSYS webpage, which is a company of lasersystems for material processing.

In both cases, traditional processes became high-priced and inaccurate comparing to laser processing. Many industries turned laser users helped by its compatibility with robots, variety of suitable materials and the quality of the terminated piece. A clear example is automobile industry, where all the processes have been extremely optimized and filled with laser robots.

Therefore, are there only advantages on this technology? The answer is no. Laser involves a large number of parameters and every application must be individually studied and optimized. The result of the work fully depends on how good these parameters have been adjusted.

On such an important technology, there is a significant focus on finding the best efficiency and results. For that end, the usual procedure is to individually optimize all the different laser parameters. When after a set of experiments one parameter is corrected, another set should be

run to correct another parameter. The process leads to long experiments which give uncertainly optimized parameters. The best quality achieved questionably matches the best quality possible, since it cannot be proved.

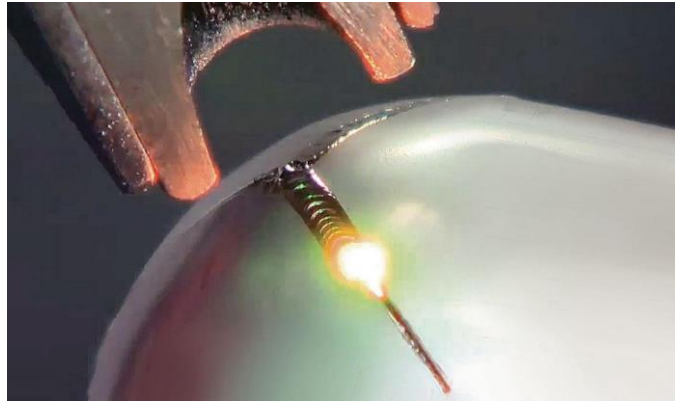


Figure 1: Laser welding.

This figure is taken from the magazine The Fabricator [31]

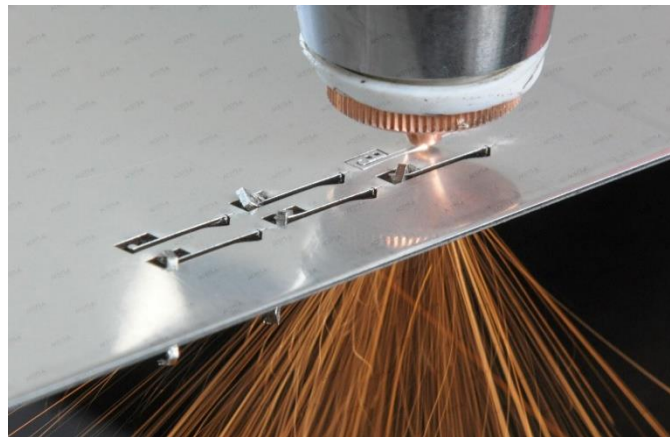


Figure 2: Laser cutting.

This figure is taken from the ACSYS website [26]

The alternative presented in this study is the Design Of Experiments (DOE), a statistical approach to the preparation of experiments based on the optimization of time and experimental runs. It helps to single out the most important factors and the different interactions between them. With its method, the number of experiments physically needed clearly decreases, meaning the cost and time required are lowered. Additionally, by its use, a formula relating the inputs and outputs can be achieved, showing which is the best quality possible and whether it is achieved or not.

The principal variables needed for this method are factors (inputs), responses (outputs) and the type of design to follow. In this study many designs will be explained, but the focus will be put into the factorial designs.

The basic steps are to select a number of factors and apply the design to them. The result will be a guide (in a matrix form) explaining how many runs the experiment needs and which are the factor values in them. When running it, the responses should be noted. At that point, the information of the factors and responses can be compared to study their relations.

The objective of this work is to evaluate the different packages that exist in R and could be used for DOE of laser processing. R is an environment mainly used for statistical computing and graphics. It is also well-known by its good manage of data storing and plotting [2] . Through this program it will be presented an interactive web application which applies DOE to laser material processing.

The version to be used of this program is RStudio 3.6.3 for Windows 64 bits.

The present document is divided as it follows:

Firstly the Design of Experiments theory is explained (**Design of experiments**). With this knowledge, a study is made of the laser process and its parameters (**Parameters considered in the laser study.**), selecting which ones will be better for the experiment.

The resulting selection was to select as inputs: the laser output power, the mode of operation (pulsed or continuous), the focal length, the processing velocity and the additional gas flow. The outputs were, for laser cutting: angularity and perpendicularity and roughness; and for laser welding: weld seam depth and hardness.

Subsequently, R program and its packages are studied (**R Packages for DOE**) in preparation for the later application of it in a web app (**Web Application.**). There, the user will be free to apply the DOE method to a personalized selection of parameters. The application will be accompanied by a manual to facilitate its use (**My Shiny App: Manual**).

2. Design of experiments

The *design of experiments* or DOE is a statistical approach to the planification of experiments. The method results in studying the relationship between inputs and outputs with the least possible effort.

This design covers mainly two aspects. The first is the *design of the experiment* itself: what variables are to be studied, which values are they given, what combinations of values are run, etc. And the second one is the *analysis of the obtained results*: which are the main effects, how do the variables relate to each other, etc. By using DOE, a study of the process parameters is done with the aim of optimizing the time and cost needed for the experiment.

These steps to take could be sum up in:

- Selecting the objective or purpose of the experiment.
- Selecting the factors or inputs and the responses or outputs.
- Selecting the experimental design. Further will be seen that the ways to approach the issue are plenty. And there is more than one type of design, each one giving different information to work with.
- Running the experiment.
- Analysing the results, studying the relations between inputs and outputs.

Being experiments such a common thing in the science world, the importance of this optimizing process is more than clear. The areas where this method has popularized more are the ones where the time required for an experiment is larger. A good example is Chemistry, where in some cases the samples have to wait for a few days to be tested. Engineering field has also applied this method, and not only due to the time gain but also for the cost effectiveness, avoiding expensive measures between others.

In the present study, DOE steps will be deeply explained and applied to the subject of matter: laser material processing.

The objective

The first thing to identify is what is the aim with this experiment. The fact of pointing out what is wanted to know is not something only related to the design of experiments. When conducting any other experiment this is also the first question whose answer should be given.

In the case of study, the objective is to maximize the quality of the laser process of cutting and welding. The quality itself is a wide and not measurable term. But for that will be named a lot of output variables which are numerical and dictate the process quality. The true objective is not only these variables to accomplish the quality norm, but also to be as positive and optimized as possible. In general terms, the aim is to optimize the general quality output variables.

Select Factors

In the design of experiments, the inputs or independent variables are called *factors* or *X* variables. And the certain values or settings they have are called *levels*. The variety of level types is wide: the levels can either be quantitative, when the variables to study are continuous; or qualitative, when there is no order on the levels. Simultaneously, they can also be numerical or nominal when levels correspond to characters or words.

The number of inputs is determined by the interest and scope of the investigation. Fewer variables generally lower the cost and time of the experiment, while they do low the potential information received too. It must be decided until what point it is worthy to study the variables. There are multiple methods for lowering the variables of your experiment, but in some cases a general DOE is applied first to identify the main effects, and then a more specific one is used to deeply understand this main effects.

No matter how, generally a selection of the most important variables is recommended. In addition, special attention should be put into the ensurement that every factor has to be easy to modify and to measure and not economically expensive to do so.

Back to the terminology, when a factor is at a specified level that is a *treatment*. And when a combination of treatments is decided, a determined level for every factor, and there is a planning on doing the experiment with this combination, that is a *run*.

The factors related to our process were selected in the section 3, '**Input parameters**'.

On the other hand, the output variables are called *responses* or *Y* variables. Unlike the factors, the responses must be numerical and quantitative values. The reason is simple: a statistical model must be applicated, where mean and deviation between others are calculated. All of these analyses require numeric values. As it happened with the factors, with a fewer number of variables the final result will be easier to achieve.

Our output variables were defined in '**Output parameters**'.

The aims of the experiment is to reach a formula which relates $y = f(x)$. It represents a polynomial equation that shows the relationships between the factors x and the responses y . The ways they can relate are many. Followingly are studied linear and quadratic relations, the most used in DOE.

Lineal model

The relation between variables can fit a simple lineal model following the formula:

$$y = b_0 + \sum_{i=1}^n b_i \cdot x_i + \varepsilon$$

Where y is the response made objective of the experiment, x_i are factors and b_i are constants which values have to be determined in order to know the relations. The value n represents the number of factors and the value i each factor. The value ε is the experimental error.

This equation only shows the interactions of first order because all of the terms are lineal. By adding the term $\sum_{i=1}^{n-1} b_{i,i+1} \cdot x_i \cdot x_{i+1}$ the interactions of second order are included too. This linear model is usually used for investigating the experiment itself, to know how good, precise or robust it is [3].

Quadratic model

This relation is used in order to discover the non-linear relationships between the variables. Moreover, as it is a quadratic function, it will also be able to find and determine the maximum or the minimum of the function.

In this case, will be added to the lineal model two more addings with a second degree:

$$y = b_0 + \sum_{i=1}^n b_i \cdot x_i + \sum_{i=1}^{n-1} b_{i,i+1} \cdot x_i \cdot x_{i+1} + \sum_{i=1}^n b_{i,i} \cdot x_i^2 + \varepsilon$$

The number of degrees of the response could still increase. Nevertheless, the experiment is usually done with the assumption that only low order interactions are important for the result, so three-degree polynomials are odd to see. They are usually left out of the model. As was said before, the number of variables of both factors and response should be really good selected, in order to only focus on the relevant

Select the Experimental Design

The way to approach the experiment depends on the objective of the experiment and on the number of factors you contemplate. Once both have already been selected, the next thing to decide is the combination of their possible values.

It could be a random selection of the levels of the factors, but that would not be reliable, as it has no scientific base but the luck to find the most interesting miscellanea. It could also be the individual variation of all the factors, but the interactions between factors would not appear in the result, providing a picture distant from the reality. Therefore, the scientific approach to the factors' combination is the factorial experimental design [4].

Factorial experimental designs consist on the multiple variation of factors at a time. This design has two characteristics that beats the disadvantages of the others approaches.

In first place, the matrix generated for the different levels and factors is symmetric and orthogonal. This matrix has for columns the different factors, and the rows are the runs of the experiment. It is called a design balanced when the matrix is symmetrical, meaning not only that all the factors have the same number of levels, but also that every treatment appears inside every block a determinate number of times. On the other hand, the orthogonality of the vectors that form the matrix ensure that the effect of a factor can be measured independently. Meaning any interaction will not change if any other factor is eliminated.

Secondly, as the variation of levels are simultaneous, the interaction between factors clearly affects the results. This knowledge leads us to a more precise answer. It can be understood how the experiment could be applied more generally, with wider boundaries. As it is more information for the same number of runs, this process is considered to be the most efficient one [3].

There are also two conditions that should be mentioned in DOE. Every experiment is recommended to contain replication and blocking.

By *replication* it is meant the repetition of the runs. By redoing a certain treatment, the results can be assured and not left to chance.

On the other hand, *blocking* is the fact of separating the treatments in blocks. By blocking, the contribution of irrelevant factors is eliminated. In any case, this is something that the DOE software usually already considers.

There is a wide variety of design classifications. They will be organized according to the Engineering Statistics Handbook [5]. This categorization depends on the objective and the number of factors of the design.

There are four different types. Followingly a sum up table connecting them all is attached:

Table 1: DOE methods from the Engineering Statistics Handbook [5]

Number of factors	Comparative Objective	Screening Objective	Response Surface Objective
1	Completely randomized design	-	-
2-4	Randomize block design	Full or Fractional Factorial Design	Central composite and Box-Behnken
5 or more		Fractional factorial design and Plackett-Burman	Screen to reduce the number and factors

Comparative designs. They are used for initial or affirming comparisons and their main applications are for few numbers of factors. As it can be seen in **Table 4**, there are two methods used.

For one factor there is *completely randomized design*, where the levels of the factor are randomly assigned. For more than one factor, the situation is having one factor of primary interest and other factors that want to be compared with the first one. The approach is called *randomize block design*, and briefly, it randomly divides the main factor levels into blocks or sets of treatments. There, the not important variables are almost constant, not affecting the experiment.

Screening designs. This experiment is usually run to identifying important factors though its interactions with the responses. It is also used when the number of factors is high, as it can be seen in **Table 4**.

With this type of methods the gain is that the number of experimental runs evidently lows. But for lowing the runs, the loss is that only will be known the main effects, and not the second level interactions. Screening design involves the two most famous design followingly explained: full and fractional factorial design.

The full factorial design: In this design, the way to obtain the number of experiments is by multiplying all the levels of all the factors involved. Usually, the number of levels is the same for every factor, so it can be expressed by the number of levels to the power of the number of factors. To make it clear, if the number of levels is 2, the equation that will lead us to the answer is 2^k , being k the number of factors.

The problem comes when the number of repetitions or runs is still very high, and it needs to be lowed for an optimisation of the process. Here it is when fractional designs appears.

The fractional factorial design: In this case only some of the previous runs will be examined. In order to know the number of experiments, the levels of factors will be elevated to the number of factors minus a fraction. Therefore the equation will be something like: 2^{k-p} .

Plackett-Burman Design: For a large number of variables these are the most used experiments. They are very efficient designs that can run up to 27 factors in 28 runs.

Response surface modelling. Also known as *RSM*, are to reach objectives like a specific target, a maximum or a minimum. But also for reducing the variation or increasing the robustness of the design.

For that, there is a necessity to make use of a second-degree polynomial model. Compared to the previous one, this means that it will not only get the main effects but also some interactions between variables. Nevertheless, as not every process is exactly quadratically approachable, this method is only an approximation of the real process. Meaning errors are already assumed. For a closer approximation, knowing the limits of the factors could help in order to start the design.

Central composite designs: Can be found inner RSM for few factors. It is also known as Box-Wilson and it examines a virtual 3D square — in the case of a 3-factorial design, any other added factor will add another dimension to the square— which every dimension is a different factor. Points are homogenously placed along the edges, and their places represent the value to take for each factor. Depending on the distribution of these points, there are different submethods.

Box-Benken designs: In this specific design, compared to the central composite, the points are placed in the middle of the edges, plus one in the centre.

If the number of parameters is excessive, there should be a step back into screening designs to first select the most important variables to later hit their targets with RSM.

For what our study concerns, further will be seen that the number of factors is moving around 2 to 5. Therefore the best range would be the middle one, from 2 to 4. Ideally, the following range could be taken into account.

As for the objective, all seem quite appealing, putting special attention into screening objective and response surface modelling. The truly objective of the study is to know the relations between the factors and responses. To find a formula which relates them. Undoubtedly, it matches the definition of screening objective, which *“identifies important factors though its interactions with the responses”*. This method is the one which will be presented in the study, because it is the one which fits more with the aim.

Nevertheless, response surface modelling is highlighted due to its importance for further improvements.

3. Parameters considered in the laser study.

As mentioned in the introduction, laser technology involves a lot of different parameters that should be studied. They will be presented in this section and divided into inputs — or independent variables — and outputs — the dependent ones —.

In order to establish an order of magnitude, reference values are to be given in every parameter. It must be mentioned that the parameters are for any laser type, but not their reference values. These references have been concretized for CO₂ lasers and may change if the laser does. The reason for choosing these lasers is they are currently the most used lasers in the processing of materials industry, and the prediction is to remain the same for several following years. Therefore, there is a wide possibility to find a match with these values.

3.1. Input parameters

The input parameters are the independent variables of the system that are able to be changed. Certainly, depending on the input selection of values different combinations of results will be obtained, which means different output values.

Followingly, the input variables will be described with detail. It must be kept in mind that later in the design of experiments only the most important variables are going to be selected, according to the viability and profits of the parameter change. The variables chosen should give relevant information to the experiment, relatively easy to change and economically possible to do so.

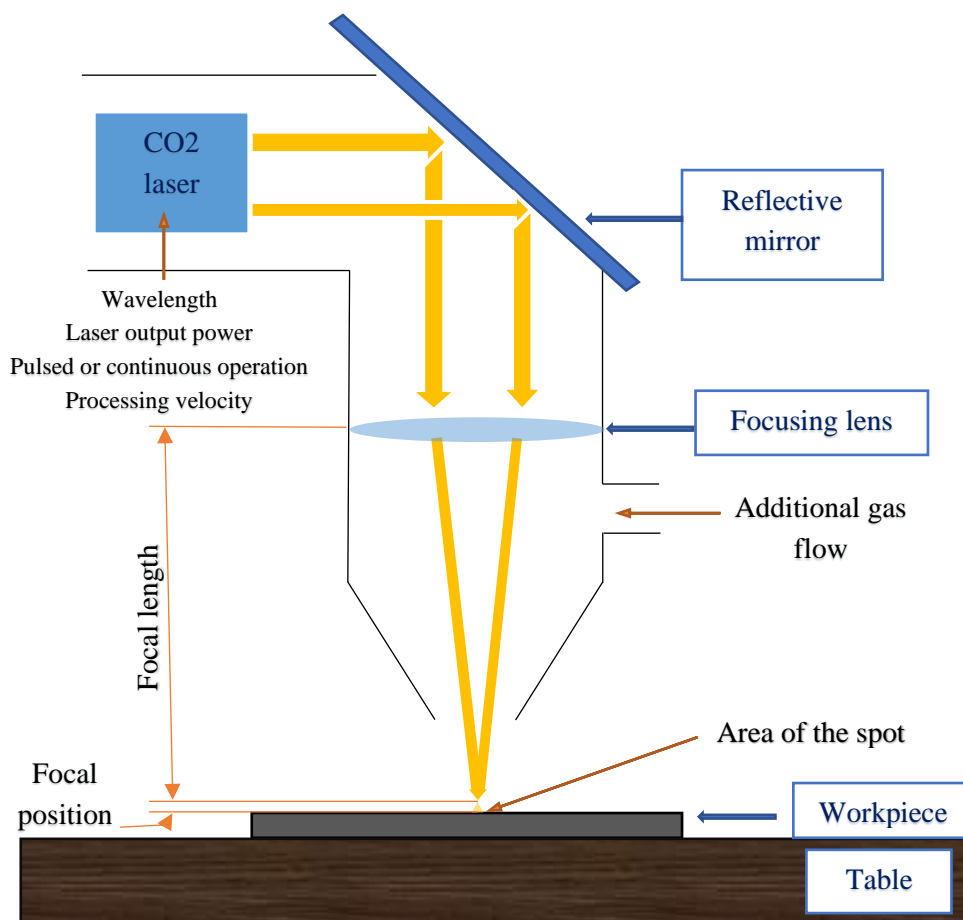


Figure 3: Scheme of a laser

Additionally, the choice will be backed up by some studies which at some point had to consider input laser variables too and, as this study does, had to decide which ones did they want to select.

In order to help the explanation of inputs, a scheme of the laser was created in the following Figure 3. There, all the inputs seen in this chapter will be included with black lettering and orange arrows. This figure will be repeatedly cited and explained in the following subsections where each input is described.

On the grounds of this, the selection of laser input parameters is:

- **Wavelength of the laser radiation (λ)**

The wavelength refers to the longitude of the phase of the light wave. Being equivalent to the frequency, as they are related by the formula $\lambda = c \cdot f$, being f frequency and c the speed of light.

On the Figure 3, this parameter appears on the laser's "black box". The inner process of a laser, involving oscillator and amplifier, is not the topic of this document. To avoid explaining it, a blue box was created to represent it. In this process is determined the wavelength of the laser.

The interactions between this specification and the other inputs are focused in the absorption of the workpiece. There should be a match between the wavelength of the laser and the absorption of the workpiece, in order to obtain a elevate efficiency. In the Figure 4 the absorption rate for different materials at different wavelengths is shown. There can be seen that the absorption of most metals is quite low around infrared light, in the range of 700nm to 1.1 μ m). Within those limits is CO₂, exactly with 10.6 μ m).

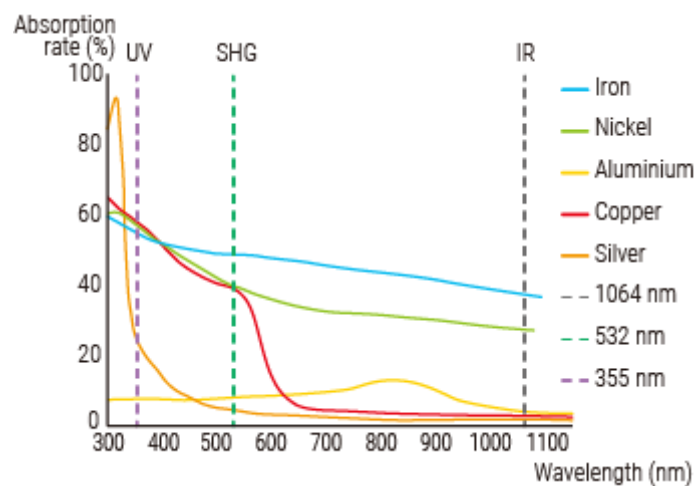


Figure 4: Light wavelength vs. metal absorption rate [32]

In any case, this parameter is determined by the laser to be had. Unlike the ones coming, it is unable to change once a laser model has been selected. This aspect lows the interest on the experiments are usually done with only one laser and the wavelength is not modified.

Therefore, this parameter will not be considered in the DOE. It is assumed that all the experiments will be run with the same laser, and therefore the same wavelength.

- **Laser output power (P)**

The output power is the parameter that usually describes the laser. In a technique meaning, it refers to the energy given by the beam divided the time of this action.

This parameter is also included in the laser “black box” in the Figure 3.

When talking about the power of a laser, it can either be the average power (mean of the power over the time of operation) or the peak power (power during a pulse). In this paper the focus will be on the first, the average power output. Its reference values for a CO₂ laser are from 1 kW up to 10 kW [6].

By all means, the intention is to obtain a power as high as possible. As many variables depend on power, increasing power will broaden the process boundaries. Some examples are the increment of the depth of penetration (leading to a thicker workpiece or harder materials) and the speed increase of process velocity [7]

The variation of the power of the laser is also easy. There is a simple and conventional regulating system for each laser. It directly changes the power to the desired one, even during the operation.

The importance of this parameter relies on its modifiability and its effects on other parameters. This makes it one of the most included in laser designs of experiments. With no doubt, it will also be included in the present study.

- **Pulsed or continuous operation**

This parameter focuses on the way the radiation is emitted. With a continuous operation, a constant radiation is emitted. While a pulsed operation involves repeated peaks of power in a certain frequency. This is usually achieved by PWM (power width modulation).

The mode of operation is determined in the laser “black box” in the Figure 3.

The normal use of lasers is with continuous waves radiation. Nevertheless, the pulsed operation might be useful in some cases. The continuous wave is used for achieving high processing velocities at high power. When the heating is not sufficiently ensured, a pulsed operation is recommended. For achieving a great quality with pulsed operation, the power and the velocity will low [7] .

This decrease can be explained with the Figure 5, where a PWM wave can be seen. The x-axis is the time, and the y-axis is the power. Two levels are differentiated in the y-axis: the high-power level, which time matches “Duty”; and the low-power level, which matches the difference between duty and period.

The relation between the pulsed operation and the other parameters lays on the pulse width, or the “Duty” period. By decreasing it, and therefore increasing the off-time (or low-power level), the average power will decrease too. If 50% of the total period was given to “Duty”, the average power output will end up being 50% of the cw-power. Additionally, as commented before, power is directly proportional to velocity. So it will decrease too.

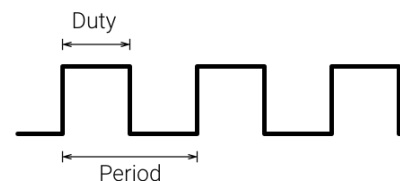


Figure 5: Pulse Width Modulation
Image from programming website [33]

Depending on the laser, the variation can be wider. Calling on a summary given in the Handbook of the Eurolaser Academy [6], by 1998 the pulse modes were from 0 to 100 KHz of frequency and from 10 μ s to infinite (continuous wave) of PWM.

The method of variation for this parameter is also simple and costless — once you have selected a laser with both continuous and pulsed operations —.

The ease of variation and effects of this parameter make it a good candidate for DOE, so it will be included in the study.

- **Focal length (F)**

The focal length of the laser is the distance needed for the lens to focus the laser beam. Physically, it is the space bounded between the position of the lens and the point in the space where the focus is.

When the focal length matches the distance between the lens and the workpiece, which equals matching the focal position to zero, the smallest spot diameter of the beam is achieved. This area is clearly having a quality effect at the end of the process, which is our objective in the design.

In the Figure 3, the focal length can be seen in the middle-lower left part, between the focusing lens and the focus point, symbolized by the end of the yellow light arrows. Please note that in this case the focus point is not matching the workpiece, so the best quality is not achieved. That was meant to include a focal position different from zero.

The reference values can change depending on the application. For the processes studied in this paper: reference cutting values go from 63.5 mm (2.5") to 190.5 mm (7.5"), while welding references are assumed to be from 100 mm to 300mm.

Modifying this value is a drawback of this parameter. It can only be properly modified during operation with scanner optics. Once the laser is stopped, the variation is simplified to a change of the lens. In this case, the length will depend on the available lenses and will not be completely customizable.

- **Focal position (δf)**

It is the distance between the point in the space where the laser beam focuses and the workpiece surface.

It should be mentioned that this distance can have any value both positive and negative. The value depends on where is the focusing spot in relation to the surface. The Figure 6 is attached for a clearer explanation. In the left case, the spot is below and further than the surface, so the focal distance takes a negative value. Contrary, in the right case the focus is above the surface and closer to the lens, so the distance will be positive. The middle case is when the focused spot matches the workpiece surface, with a distance equal to zero. As it was said, this is the desired value for achieving the best quality.

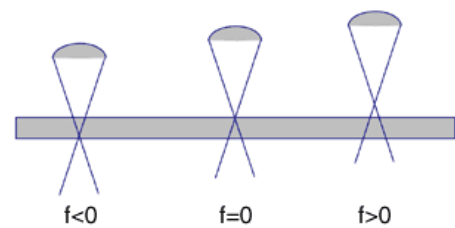


Figure 6: Focal distance
Image from ESAB [34]

In the Figure 3, the focal position is on the lower left part of the image. In that case the distance is positive.

The focal position is related to the laser intensity [W/cm^2] parameter. This parameter is an indicator of how much power per area it is been released, pointing to the potential of the laser and determining the upper limits of the laser work. By varying either power or focal position — and therefore the area of the beam — the intensity is affected [8]. It consequently affects the penetration depth.

The value of the parameter itself, closer to zero for a better quality, together with its influence on the laser intensity, highlight the importance of the parameter. Nevertheless, for adjusting this parameter, the previous input must be changed too, creating both the same effects. Consequently, only one of the two parameters should be considered for the design. Taking into account the ease of measurement, the previous parameter is a better candidate.

- **Area of the spot on the sample surface**

It is the area of laser in the workpiece surface. As a usually circular area, this parameter can be referred as the diameter or radius too.

As mentioned above, it is determined by both focal length and position. But it also depends on the laser beam itself and its quality.

In the Figure 3 the area is pointed out with an orange arrow in the bottom part of the image. From the perspective taken, it cannot be clearly seen. Just the horizontal projection is visible. From an upper cut view, the area should be seen better.

In the case of the figure, the smallest area possible is not achieved. That spot is little higher than the workpiece surface. Once this point is surpassed, the area increases.

Despite the importance of this parameter, it is intimately related to the two previous ones. Focusing on the ease to change and measure them, this parameter will not be determined for the experiments.

- **Processing velocity**

As the name mentions, this parameter refers to how fast the operation by the laser is done, the length processed per unit of time.

It is difficult to tell where in Figure 3 it is. The value of the parameter is decided in the laser black box, but its effect appears in the workpiece. As the laser is where it is firstly decided, that is the place in the figure where it was indicated.

Even incrementing the velocity tends to elevate the productivity, it also affects heating and cooling cycles badly. Indeed, it can be negative for the porosity of the welding, which makes a clear effect on the quality of the workpiece, our objective. In some materials, a very high cooling rate, by a very high processing velocity, can get to increase the number of pores in a weld seam. This is because the gas bubbles are trapped in the melt and have not enough time to reach the surface.

Together with the laser output power determine the *line of energy input* (J/m) on the sample, another interesting parameter of lasers. This connection with other parameters, like the power output, and its importance to our main target convert this parameter into a great candidate for the design of experiments.

The range of velocities is from stop, which is counted as a boundary but does not help the process itself, up to several 100 m/min.

- **Additional gas flow**

It refers to the auxiliary flow of gas in the process. This additional flux helps the operation of material processing.

Contrary to some of the previous parameters mentioned, that are equivalent for any process, this parameter is an exception. Depending on what operation is being done, whether is it being welded or cut, the effect will be different:

When *welding* with laser, the benefit of using extra gas is preventing the oxidation of the weld seam. In this case both the gas type and the flow rate (L/min) of it must be determined. For welding, the most used gases are Nitrogen, Argon or Helium. This last one with better results but higher price. --For laser welding the flow is quite small, being around 10 litres per minute.

When *cutting*, adding more gas will chemically react and give more energy to the laser process. In this context there is a few types of lasers depending on the type of the added gas. They are classified depending on whether the gas is active or inert.

Basically, there are *oxygen* laser cutting, where the gas reacts with the material and it is burnt and vaporised. In these lasers, the quality is not the best as cut edges end oxidized. Therefore, their mainly uses are for construction steels. The oxygen laser cutting can be performed with CO₂ or solid-state lasers. The reference values of flow are low with low pressures. The usual flow is approximately up to 50 l/min [7].

On the opposite, there are *nitrogen* laser cutting. In those, the gas does not react, so the molten material is expelled preventing the oxidation of the cut kerf. This type of lasers is principally used for stainless steel as their quality is higher. With nitrogen, the gas flow raises due to the rise of pressure up to 30 bars, it can be up to 120 l/min [7].

Mentioning quality several times during the definition helps to realize how important this parameter is. It is clear to see that this parameter, in terms of how much quantity is it used, will also be considered.

To sum up, the most important factors for laser material processing are laser output power, pulsed or continuous operation, focal length, processing velocity and additional gas flow. The not considered factors are wavelength, for the difficult that presents changing the value, and focal position so as the area of the laser spot, for being excessively related with focal length.

As laser technology had such a reiterative study, there is so many authors who had already studied the affecting parameters. Here there are some examples, all of them related to material processing:

Babu, Buvanashakaran and Balasubramanian [9] studied the laser transformation of low alloy steel, identifying power of laser beam (P) and traveling speed (v) as the major input process parameters. This study had the time and tools to physically reproduce a DOE experiment analysed via RSM, which ended up with a prediction very close to the experimental reality.

The fact of successfully running a DOE experiment pointing out two of the input variables selected in the present document, helped to confirm the choice of them as DOE inputs.

KT Voisey [8] determined in its book the relevant parameters to laser drilling: laser wavelength and frequency (λ); pulse width, pulse repetition rate or pulse frequency (all of them referencing PMW); average or peak power (P); fluence (the amount of energy per area, related to the intensity, which is closely linked with the area of the spot surface, the power

and the processing velocity), and the focal position. All of this considered parameters are somehow related to the chosen parameters of the present study, supporting the selection.

Sivarao, Shukor, Anand and Ammar [10] led a DOE approach to laser via RSM and determined cutting speed(v), gas pressure, pulse energy (related to power), pulse duration and pulse repetition (related to PWM) significantly influential. The study concluded relating these inputs between them and to some outputs as surface roughness. It is proposed for a checking when an experiment is run, in order to ensure the results are correct.

Lokesh, Niresh, Neelakrishnan and Deepak [11] considered three laser cutting parameters: cutting speed (v), power output and focal length. The experiment was analysed following the Taguchi method. The resulting plots are useful and clear relating these inputs to some outputs as the kerf width, further seen in this document.

It is evident that all the input parameters become important depending on what is the target, where is the focus at, what are our output parameters. These variables are what is followingly covered.

3.2. Output parameters

The output parameters are the results of the operation. So many variables could be mention in this section, but the focus is put into the values that help quantifying the quality, which is the objective of this study.

It should be recalled that the output parameters, as the inputs, must try to be easy to measure so as cost-effective.

The two different laser operations emphasized in the study have different resultant workpieces, so their quality results are differently measured. Due to this differentiation, the output parameters will be separated depending on the laser operation studied. Firstly, outputs related to laser cutting will be analysed, for later studying the ones relating laser welding.

3.2.1. For laser cutting:

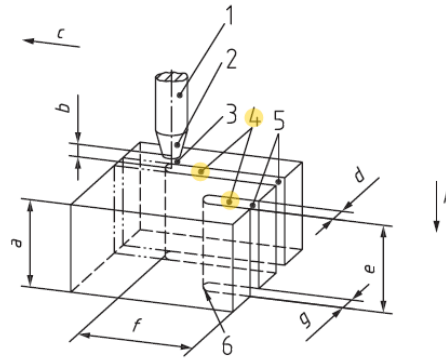
In most cases in laser cutting industry, the quality is checked by a visual examination. Nevertheless, as a scientific research and a statistical application of DOE, this study requires quantified values for quality.

This study is held up by the *standard ISO 9013:2017* [12] , which studies the quality tolerances for thermal cuts. The document contemplate several procedures, on which depend the potential achievable quality. Following the Table A.1 from the Annex A of the standard, the laser cutting matches the class 1.

The quality characteristic values according to the standard are: perpendicularity or angularity tolerance and mean height of the profile. These can be accompanied by the drag, the melting of top edge and the drop. They all are followingly presented.

For a better understanding, the kerf width term is explained previously:

The *kerf width* is the part of removed material in the piece when it is being cut. Following the standard ISO 9013 for laser cutting: “the kerf is width of the cut produced during a cutting process at the upper edge of cut or with existing melting of top edge immediately below, as caused by the cutting jet” [12]. Attached is the Figure 7 from the same standard, where the kerf width is highlighted in a drawing scheme. There the reader can have a visual concept of the term.



Key

1	torch/cutting head	a	work piece thickness
2	nozzle	b	nozzle distance
3	beam/flame/arc	c	advance direction
4	kerf	d	top kerf width
5	start of cut	e	cut thickness
6	end of cut	f	length of cut
		g	bottom kerf width
		h	cutting direction

Figure 7: Terms related to the cutting process of the work piece.
From ISO 9013:2017 [12]

The kerf is determined by many parameters. Not only the workpiece itself (thickness and material), but also many inputs as laser output power, focal length and position, velocity and gas flow. To provide some context, the range of this parameter is truly wide, going from 0.08 to 1 mm.

In this study, the kerf will not be used as an output, but many of the following parameters will derivate from it.

- **Angularity and perpendicularity:**

An example of the related parameters to the kerf is the angularity and perpendicularity of the cut. The definition given in the standard is: “distance between two parallel straight lines (tangents) between which the cut surface profile is inscribed and within the set angle (e.g. 90° in the case of vertical cuts)”. Figure 8 is attached for a visual explanation. There the reader can have a light idea of the ways in which the angularity and perpendicularity are measured in both vertical and angular cut.

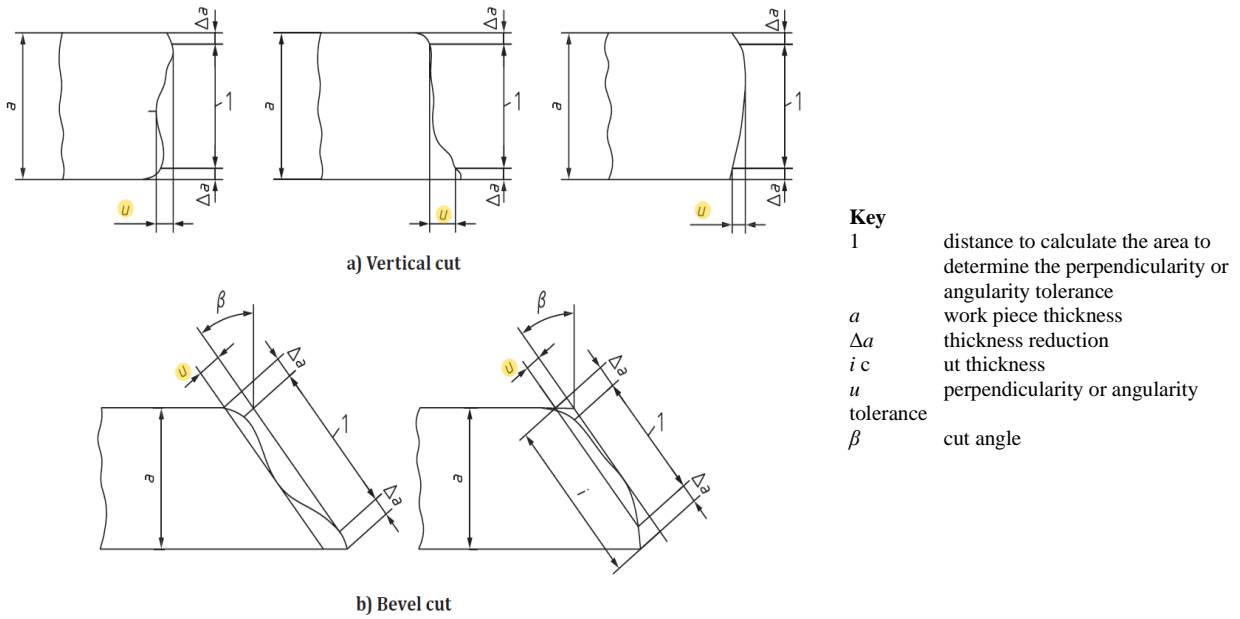
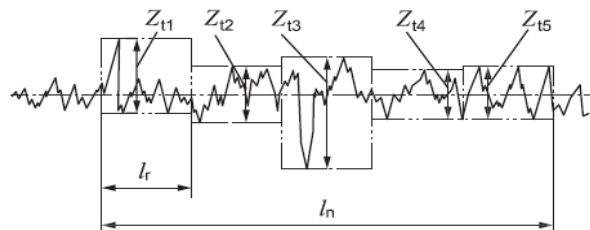


Figure 8: Perpendicularity or angularity tolerances
 From ISO 9013:2017 [12]

• **Edge roughness:**

The roughness is the amount of irregularities than a surface owns. It is measured by the periodicity and amplitude of striations in the cut surface. These striations will have a different appearance on the top, the centre or the bottom of the cut surface. The aim is to all these parts to follow the standards. In ISO 9013, the roughness is measured as the Rz5: mean height of the profile, which is: “*arithmetic mean of the single profile elements of five bordering single measured distances*” [12]. The Figure 9 is included for a better understand. The spike line represents the cut surface real profile. The dashed line is the mean of the heights. And the Z are the 5 chosen points to measure.



Key
 Z_{t1} to Z_{t5} single profile elements
 l_n evaluation length
 l_r single sampling length (1/5 of l_n)

Figure 9: Mean height of the profile.
 From ISO 9013:2017 [12]

Clearly, the lower roughness matches the highest quality of the workpiece. The maxim is the smoother the better. This parameter is said to be reduced, and therefore improved, by enhancing cutting speed and frequency, and lowering laser power and gas pressure [13].

Both angularity and perpendicularity, and roughness have the instruments to use, way of measuring and tolerances of the parameters fully described in the standard, attaching tables and graphics. The reader is redirected to the section 6 of standard for the correct procedure of the experiments.

- **Drag:**

The drag is the “projected distance between the two edges of a drag line in the direction of cutting” [12]. In the **Figure 10** some graphical examples can be seen. The first left image is a cut top view of the process, while the others are lateral views.

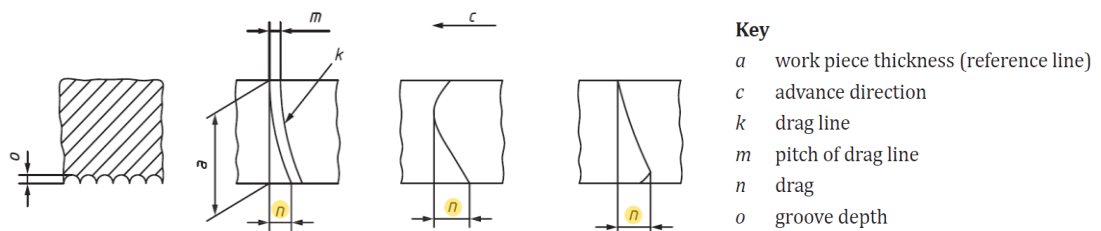


Figure 10: Drag line
From ISO 9013:2017 [12]

A visual connection can be done between this first view and the **Figure 11**. It is a drawing of the laser cutting process where the n parameter, the drag, can be more easily spotted. It is taken from a scientific article where the quality of a cut workpiece is being studied for a CO2 laser, which matches the present subject of study.

During the research made for the present study, the drag parameter has not often appeared. For this reason, this study will not deepen more into this parameter. If the reader wanted to do so, the thermal cutting standard also offers its quality values to achieve.

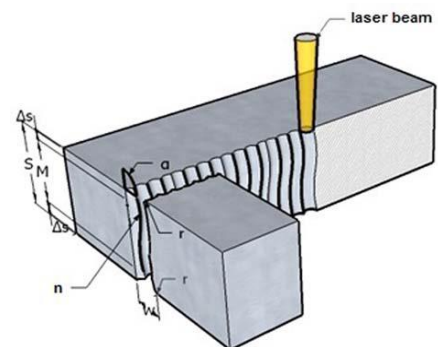


Figure 11: Parameters for laser cutting.
Article [35]

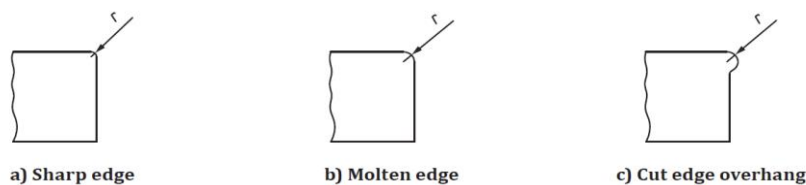


Figure 12: Melting on top edge.
From ISO 9013:2017 [12]

- **Melting on top edge:**

It is the radius characterizing the upper cut edge. Three shapes are differentiated and showed in **Figure 12**: sharp edge, molten edge or cut edge overhang. The standard fixes the radius values in function of the precision of the instrument, being either 0.05mm or 0.1mm.

Considering the complexity of measuring a radio and the small magnitude of the parameter, the study will not focus on it. It is mention not only due to its appearance on the standard but also to the formation of the reader, who can consult the standard for further information.

- **Dross:**

When cutting the piece, part of the material is being removed. If the conditions are not optimal, this material melts and remains at the bottom of the cutting edges of the piece. That is what is called burr or dross. Following the standard *ISO 9013:2017*, the dross is “*metal residue sticking to the lower part of the cut*”. In the Figure 13 from the same standard, the dross can be seen at the lower right part of the drawing, shaping a drop at the end of the cut surface (right vertical line).

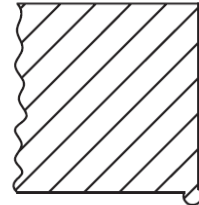


Figure 13: Dross.
From ISO 9013:2017 [12]

This parameter is related to the kerf width. Usually, if the kerf is too narrow, the roughness at the beginning of the cut is smooth but it has heavy dross at the bottom. Nevertheless, is the dross wants to be avoided by widening the kerf, the roughness of the cut will be increased.

The measurement of this parameter is only visual, checking whether there is dross or not. For a better quality of the cut, the dross is clearly avoided. In addition, as this parameter does not have a quantified value, it will be skip from the study.

Needless to say, there are many more quality parameters concerning laser cutting. For example, corrosion. While doing DOE there is a need to prioritize which are the most important variables to focus. The missing parameters will not be studied in this work due to both its importance and lack of ability of measurement. The importance has been held up by the standard, which contains the most important parameters, and the lack of measurement is missed due to the need of quantification of DOE.

3.2.2. For laser welding:

There have been created many norms welding parameters, being such a delicate procedure. Between these standards, are to stand out:

- For nomenclature of processes: *ISO 4063* [14].
- For working positions: *ISO 6947* [15].
- For equipment: *ISO 11145* [16].
- For seam quality evaluation: *ISO 13919-1* [17].
- For test and inspection: *ISO 15614 - 11*[18].
- For quality management: *ISO 9000* [19].

There are more norms for the general process of welding. Nevertheless, here this document will not need neither focus on them. They will be named only in order to concern about the finesse of the process. Some of them are: for coordinating (*ISO 14731*), for the personnel (*ISO*

14732), for specifications for the procedures of welding (*ISO 15607* and *ISO 15609 part 3-4*), for the materials involved (*Base EN 10025-3* and filler *ISO 2560*), and for the system (*ISO 15616*).

All these norms stand out that the quality of a laser welding is not as easy to see as for a laser cutting. The testing is more complicated because most of the parameters are hidden from direct observation.

In this study, a selection of outputs parameters has been done for testing the welding quality. They are explained below:

- **Weld seam width, depth and area.**

When welding, two components are joined by heat and/or pressure and with or without additional filler materials. That joint of the welding is named weld seam.

This seam could be studied from a lot of parameters: its width, its depth and its total area. Weld seam width and depth go hand in hand, as they both affect each other. So is that, it is often referenced as the general weld seam geometry. On the other hand, the area is the result of both parameters, so its relation is more than clear.

For what *width* concerns, a smaller width is preferable in most cases. That is usually related to a faster welding, optimizing the times of the process. Nevertheless, this increases the thermal gradient, causing an increase of hardness or brittleness. The aim should be to create a balance between these two interests.

The seam is naturally influenced by some input parameters, as for example laser power output and processing velocity. With a low power and speed, the width is smaller, which means better. It also helps when the focal length is medium [11]. As it happened with the laser cutting outputs, these parameters are also influenced of external parameters, as it is the workpiece. The weld seam does also depend on the components to be weld, usually being metals.

Measuring the width of the weld seam is not found to be difficult, as it is on the surface and it can be done with a non-destructive inspection.

For the *weld seam depth*, a full penetration is usually desired. This is due to the fact that the resistance of the weld will be bigger for a deeper seam. Nevertheless, this may not be required in a specific application, where the weld seam does not need to fully go through the material. Every case should be separately studied in order not to exceed the depth needed for a determined material thickness.

Figure 14 from the *standard ISO 13919-1* [17] is contemplating the depth of the weld seam in the norms. The s symbolizes the weld penetration, or depth, and the h_1 parameter is the deviation from the required weld penetration. Depending on the level of quality desired, the not-welded length is either limited to a value, or not permitted at all.

Contrary to the width, the depth requires more complex techniques. If the inspection is required not to be destructive, it can be done with radiographic or ultrasonic testing.

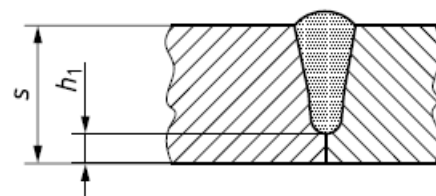


Figure 14: Lack of penetration.
From ISO 13919-1:2019 [17]

One of the principal qualities required of both width and depth is that their values should be constant over the entire length. Usually, with power and speed they both increase or decrease together. Nevertheless, there is one way to make them desynchronize it is by modifying the amplitude of the wave. With its increase, the depth lows and the width highs [20] .

To end, the *total area of the seam* is influenced by the two parameters above, the width and the depth. In order to weight the parameters, the area does not give enough information. An area by itself it is not a reference of how good a welding is, but its seam depth and width are. When considering the weld seam geometry in the study, only one of these parameters would be tested, depending on the available inspection instruments. Ideally, the depth is the best parameter to measure, but it also implies more difficult techniques. In this study, it will be assumed that those instruments are available, so it will be a chosen output parameter.

- **Area of pores**

While welding, there is a possibility that the air in the atmosphere gets stuck in the seam, which creates pores on it. In some cases the vaporized material helps this problem too. For example, in the case of the aluminium, a lot of hydrogen is solved during the melting. Hydrogen pores can latter appear during the resolidification, due to the drop of the hydrogen solubility.

This is a very important parameter due to its direct negative effects to the joint strength, another parameter that will be deepen in later. And the ways it could affect are many. It is significant not only the total area of pores but also the area of each pore, and how do they distance from each other.

The way to measure this parameter gets harder than the previous. It can be done by cross-sections, which could get to invalidate the workpiece, or by a Scanning Electron Microscope (SEM) and software, increasing the cost of the measurement a little. Both cases are time consuming processes, which are not desired. This is the reason why in this study the area of pores will not be considered an important output.

In any case, in the *ISO 13913-1* [17] the issue is boarded and many parameters are described involving it. Some examples are maximum dimension of a surface pore, root porosity, clustered porosity or linear porosity.

- **Hardness**

The hardness of a material represents its resistance to permanent surface deformation. This parameter can be divided into two ranges: microhardness (when the load applied for the test is lower than 10 Newton) and macrohardness (when the load is higher than 10). The ranges would be applied in function of the dimensions of the experiment and workpiece.

When the hardness of a material is increased in just a zone, its properties are being changed. And even it could seem a good quality for a material, the possibilities of having cracks are being increased. It is very common to have increased hardness values in laser welding, due to fast heating and cooling cycles. For avoiding this situation, it should be increased the cooling time. Which can be done by lowing the processing velocity.

On the other hand, if the weld joint is weak, there is plastic deformation when applying a load. A balance is expected and the hardness of the weld is desired to be the same as the joint materials.

The hardness is a good parameter not only by itself but also by its relation with the tensile strength, another parameter. Tensile strength and hardness are directly proportional for some

metals, as steel. The hardness conversion is described in the *ASTM A 370 Tables* for the different materials.

This makes hardness test convenient for calculating the tensile strength, because they are simple, not expensive and non-destructive, but creating a small penetration in the surface.

There are many tests for hardness, but the most popular is the Vickers hardness test. For a deeper explanation of the test, it is referenced "*Hardness Testing of Welds*" from Welding Technology Institute of Australia [21]. And the TWI Global website, which also explains this test and some others [22], [23]. Reading these references is recommended when the experiment is conducted.

- **Joint strength**

Already mentioned in the previous parameter, the tensile strength is the tensile strength of the joint. The resistance of a material to breaking under tension. As one would expect, it is being looked for a high value of joint strength. Indeed, in some cases a minimum value is required.

Even this is one of the most important quality parameters, directly testing it cannot be done in all the examples. Luckily, it can be calculated from the hardness. The parameter is also related to many other output parameters. For example, an adequate weld seam geometry, low area of pores and high hardness raise the strength of the piece.

From the seen laser welding outputs, a selection should be done for the DOE experiment. Following the reasoning in each parameter, weld seam depth and hardness will be the measured parameters. Additionally, if the reader is interested in the joint strength, a calculation from the hardness will be done.

In order to sum up the whole section, the parameters chosen are presented in a sum up table. Table 1 shows the inputs and its limit values.

Table 2: Summary of the factors.

x_i	Factor	Values
x_1	Laser output power	from 1 to 10 kW
x_2	Pulsed or continuous operation	from 10 μ s (PW) to ∞ (CW)
x_3	Focal position	Cutting: 60-190 mm, Welding: 100-300 mm
x_4	Processing velocity	Values from 0 (stop) to 100 m/min.
x_5	Additional gas flow	Cutting: 50-120 l/min, Welding: 10 l/min

While the responses selected for laser cutting and laser welding are determined in **Table 3** and **Table 4**:

Table 3: Summary of the responses for laser cutting

y_i	Response
y_1	Angularity and Perpendicularity
y_2	Edge roughness

Table 4: Summary of the responses for laser welding

y_i	Response
y_1	Weld seam width
y_2	Hardness

4. R Packages for DOE

To apply the design of experiments, it will be used a statistical program called R [24], mentioned in the introduction. The reason to use a statistical program for this experiment is because the ambit of design of experiments was born in the statistical world. And not only the designs but also the later analysis of the data is intimately proximate to statistics.

The R software can be accompanied by many personalised packages depending on the area of interest. The Comprehensive R Archive Network (CRAN), network and web servers for R, stores all the downloading versions of the different R programs and packages, so as the documentation for its use. The number of R packages available right now in the web page is around 10.000 units. To concrete the research, in 2008 CRAN Task View was created. Inside CRAN webpage, it focuses your research on a certain topic, and it shows the packages believed to be more used and helpful for it.

Between the large number of packages there are some directly focused in DOE [25]. The creation of these packages has been constantly growing since the beginning of its use. Figure 15 shown below presents the evolution of the increment of DOE packages in the last years.

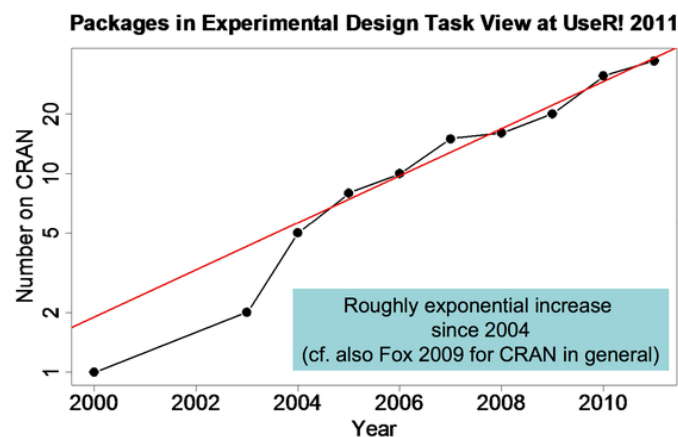


Figure 15: R Packages for DOE in time
Reference: Design of Experiments in R - Prof. Ulrike Grompling [36]

In this section some of the DOE package will be presented and discussed, in order to highlight their advantages and downsides.

4.1. DoE.base and RcmdrPlugin.DoE

The most used and specialized package for screening design of experiments is *DoE.base: Full Factorials, Orthogonal Arrays and Base Utilities for DoE Packages*.

This package is used for the creation of designs and its analysis. It is focused on creating a wide variety of design, as it can be seen in the Figure 16, among which stand out full factorial designs and orthogonal arrays-based designs.

As for the analysis aspect, the package includes a big plotting infrastructure that will be followingly commented.

Doe.base is part of a five-package kit for industrial experimentation, where can also be found: *DoE.MIOarray* for creating orthogonal arrays, *FrF2* for fractional designs of 2 levels, and it can be enhanced with *FrF2.catlg128* up to 128 runs. *DoE.wrapper* for design functionality and *RcmdrPlugin* as a GUI. What will be studied in this section is the whole kit and not isolated packages. Nevertheless, it should be mentioned that *Doe.base* and *FrF2* are the most used packages and they are frequently used separately.

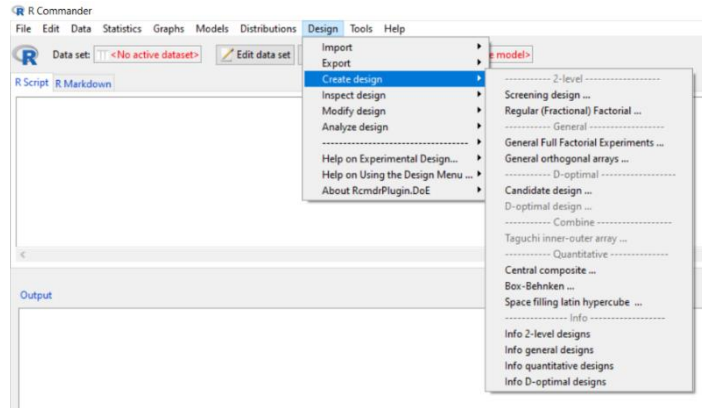


Figure 16: RcmdrPlugin.DoE's possibilities of design.

The easiest way to interact with this five-package kit is through the graphical user interface, as it could already be seen in Figure 16. This is definitely the highlight of the kit, making it available for both experts in the topic or not and creating a big difference with the rest of the packages.

Regardless, if the user prefers to use the packages separately entering the code through R, it is also available. For that, CRAN provides a pdf manual explaining the functions that they contain.

Following the GUI in order to create a design simply and successfully, the first step is choosing the desired method. Depending on this choice, it will be asked to fulfil a new window with factors, levels, numbers of blocks, randomization, etc. Once all the information is completed, the different runs with the factor values will instantly appear in data visualization.

As an example, for a 2-level Fractional design with our laser variables. The recommended experiments to run are shown in the following figure. (Figure 17)

The image shows a window titled 'Design.1.withcenterpts' displaying a table of design runs. The table has 8 rows and 6 columns: Laser_output, CW, PW, Focal_length, Processing_velocity, and Gas_flow. The values are as follows:

	Laser_output	CW	PW	Focal_length	Processing_velocity	Gas_flow
1	1	-1	1	1	-1	1
2	1	1	-1	-1	1	-1
3	-1	-1	1	1	1	-1
4	-1	-1	-1	-1	1	1
5	1	1	1	1	1	1
6	1	-1	-1	-1	-1	-1
7	-1	1	1	1	-1	-1
8	-1	1	-1	-1	-1	1

Figure 17: Fractional design runs.

The indirect data as centre points or replications was asked in the information. In any case, the later modification is effortless. In the modify design section you are able to add, for example, centre points with the desired symmetrical distribution. And in Data Edit any run can be overwritten or deleted. Letting the scientist to have the last word.

Another of the advantages of this package is that is also the user who decides the levels of a parameter. Experienced DOE professionals know that for a 2-level fractional design, the levels are identified as +1 for the high and -1 for the low, even this does not match the reality of the inputs. Explained in other words, generally the parameters do not take the value of ± 1 .

Taking the laser output power as an example. Their values go from to 10 kW. Their levels are 1 and 10, but they will be referred as the high (10) and the low (1). In this case, when a +1 appears for laser power, it will mean that a value of 10kW should be tested. It might be believed to be a no-sense change unless the user is already used to that nomenclature.

If not, Doe.base gives the opportunity to choose the level values in case the user prefers to use the real limit values of the parameters.

Once all the inputs are introduced, and the experiments have been physically run, a file with the responses can be loaded. At this point the results can be studied and analysed.

The following figures are a demonstration of the multiple analysis that can be done with this powerful package. For plotting results, as shown in **Figure 18**, the variety is wide, with the possibility of studying the relations between variables not only in two dimensions, but also in three. On the subject of analyses all the most important statistic variables are able to specify in the drop-down list of **Figure 19**. The distribution variety is ample and very personalized, as it can be seen in figures **Figure 21** and **Figure 20**. Specially, there is a reason to highlight in Statistics the model adjustment, where a lineal regression can be suit to the model. Meaning it will be found a formula $y = f(x)$ which relates the inputs with the outputs, being the aim of this whole experiment.

All in all, this package is believed to be well equipped. Not only do the options displayed offer a wide variety in the creation of design but they also do in the later analysis. The data collection is simple, offering many personalization all over the procedure, so as the later importation of responses, supporting different file formats. Not to forget that the biggest highlight, as it was before said, is the graphical user interface that approaches the design of experiments to more audiences.

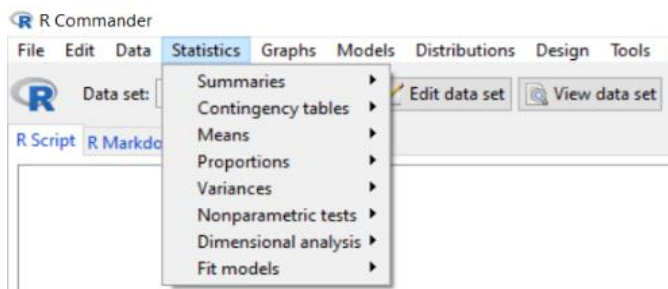


Figure 19: Statistic Options in RcmdrPlugin.Doe

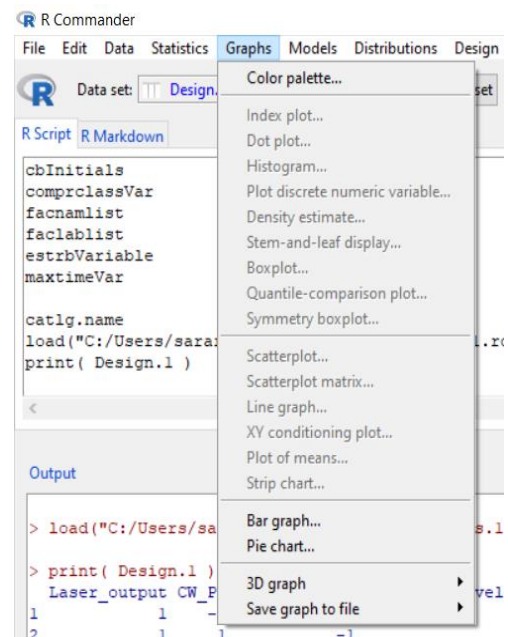


Figure 18: Graphical Options in RcmdrPlugin.Doe.

With no surprise, this package is understandable the most used one for industrial experiments, and it will be a decisive guidance for the creation of our laser web app.

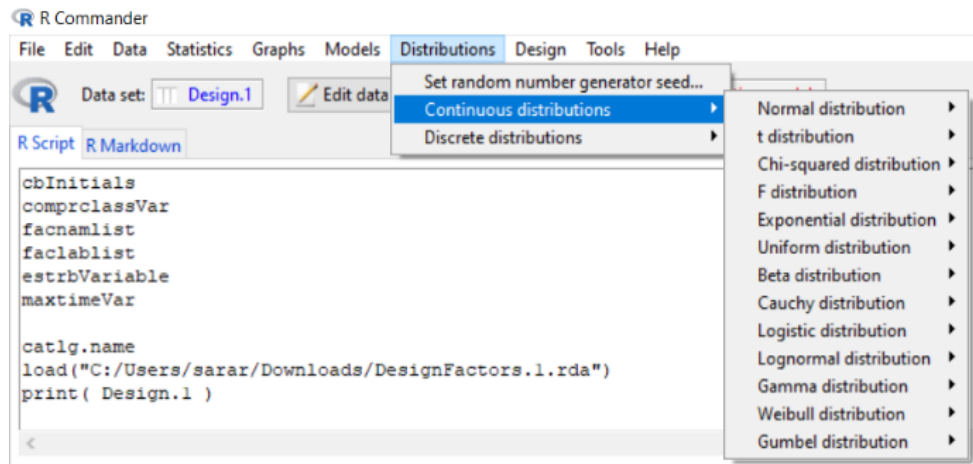


Figure 21: Continuous distributions in RcmdrPlugin.DoE

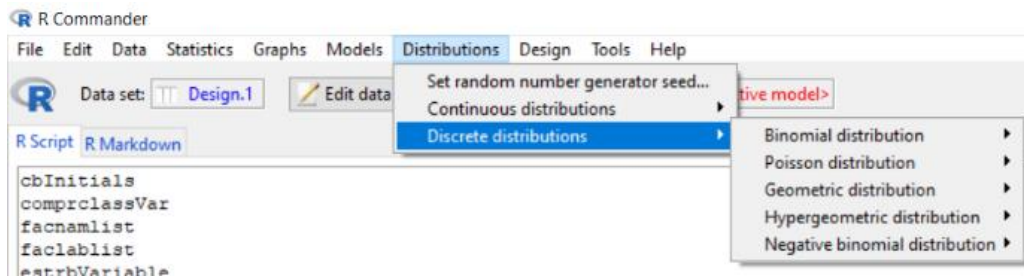


Figure 20: Discrete distributions in RcmdrPlugin.DoE

4.2. Planor

Another package similar to the previous one is *planor: Generation of Regular Factorial Designs*. While *Doe.base* was more focused in full factorial designs, this package does so with the generation of factorial fractional designs. Apart from that, it does also contemplate orthogonal blocks and plot generation.

The differences between them lay on the fact that *Doe.base* is more permissible with the creation of non-regular designs, and the diversity of criteria used for the analyses, while on the other hand, *planor* allows to specify the factors to control and the ANOVA model to use when analysing the results.

One of the clear disadvantages of this model is the lack of a graphical interface. In this case, formulas and commands should be entered for entering the values and choices made. That means that the package is geared mainly towards a professional sector.

It should be also mention that even they did not add the graphical interface, they did add some shortcuts for the creation of the design.

There is an easier formula that creates a basic design called *regular.design* whose arguments are the name of the factors, their levels, the main model formula which relates the factors — following the syntaxis of the **Lineal** model but without specifying the constants that accompany the factor, as we do not know them yet—, the number of blocks, or runs (units) and

the option to randomize, between many others. With a few required arguments, the package quickly generates the design matrix.

For a fractional design of 2^{5-1} units, with no blocks and no randomization — in favour of simplifying the experiment as much as possible — the planor results are:

```
f.names=c("LOP", "PCO", "FL", "PV", "GI")
mydesign <- regular.design(factors=f.names, nlevels=rep(2,5), model=~(LOP+PCO+FL+PV+GI)^2,
estimate=~LOP+PCO+FL+PV+GI, nunits=2^4)
## The search is closed: max.sol = 1 solution(s) found
print(mydesign)
## An object of class "planordesign"
## Slot "design":
##   LOP PCO FL PV GI
## 1  1  1  1  1  1
## 2  1  1  1  1  2
## 3  1  1  2  2  1
## 4  1  1  2  2  2
## 5  1  2  1  2  1
## 6  1  2  1  2  2
## 7  1  2  2  1  1
## 8  1  2  2  1  2
## 9  2  1  1  2  1
## 10 2  1  1  2  2
## 11 2  1  2  1  1
## 12 2  1  2  1  2
## 13 2  2  1  1  1
## 14 2  2  1  1  2
## 15 2  2  2  2  1
## 16 2  2  2  2  2
```

For this design, the name of the factors was chosen as the initials of the laser inputs.

In any case, the CRAN webpage also provides a manual for the coding options [26], as it does with every package, where we can find the different codes to use with this package. If *regular.design* does not seem to be a solution for us, further steps and personalization can be taken following this manual.

4.3. Other packages

Searching for DOE in the CRAN Task View, allows you to see all the different packages related to it. Inner DOE, they are also directed to different purposes: from industrial to agricultural experiments, going through computer, chemistry and healthcare too. [26]

None of them has a graphical interface as the first package studied, so their uses are generally more difficult.

A thing in what they unite is that most of them, as we will see below are a supplement of a book or course, where all the mathematical aspects are explained. Therefore, it is understandable that the packages are mainly professional focused and there is no need of a graphical user interface. Indeed, apart from RcmdrPlugin there is only one. It is the *GroupSeq* [26] serving as the GUI for *gsDesign* [26], both for probability of group sequential designs centred in clinical trials.

Many of the packages are focussed in a narrow ambit. Nevertheless, that is not a problem due to the possibility of combining many packages in the R code.

Some more examples of DOE packages are:

"BHH2: Useful functions for Box, Hunter and Hunter II", named after the writers of a box to which the package accompanies. It works like FrF2 on creating and analysing Fractional Factorial designs but less comfortable. The ANOVA analysis is one of its highlights [26]. Similarly, the package "pid: Process Improvement using Data" also takes 2-level fractional design knowledge from that book and it accompanies an online course called "Experimentation for Improvement" in Coursera. [26]

For 2-level fractional designs, the most used designs in industry, it can also be found the package *"BsMD: Bayes Screening and Model Discrimination"*, which accompanies the book of Mayer, Stainberg and Box, 1996. This one is more focused on the analysis of the data through Bayesian charts. [26]

Also *"FMC: Factorial Experiments with Minimum Level Changes"* which focuses on the factor changes needed between runs. The runs are ordered following the least changes between them, so as to save more time and cost. [26]

And as an example of another variety, for the optimization it exists *"rsm: Response-Surface Analysis"* that creates and analyses them following "Experiments: Planning, Analysis, and Parameter Design Optimization" (2009). [26]

5. Web Application.

A web interface was created to facilitate the design of experiments in laser. The aim of this app is to apply everything that was explained through this document.

For the development of the application, the program used was R (Windows 64 bits version 3.6.3) with some packages. For the main aspects, the packages used were *shiny* [27] for developing the app and *shinydashboard* [26] for a nicer interface look. Other packages were used for more concrete situations. For example, *DoE.base* [26] and *FrF2* [27], already explained in section 4.1 were needed for creating the DOE matrix. And the package *shinyMatrix* [26] was used only at one point for generating a matrix that the user can modify with inputs. Similar as the previous, *DT* [28] was used for printing tables in the user interface. To finish, *ggplot2* [29] and *corrplot* [30] were used for the generation of the plots.

The development and performance of the web application will be explained in this section. Certainly, to fully understand it a basic level of programming is needed. In any case, its content has been found useful. Not only to understand the behaviour of the program, but also to help further improvements.

In terms of programming, the application needs two files or components called ui and server. The *user interface* or ui handles the layout and appearance, while the *server* encloses the functions and instructions needed for the proper running of the application. The server is in charge of the hidden code and operations, throughout the time the ui contains information about what will be shown in the page.

In the case of these study, two files are created, assembling ui and server. For facilitating the use of the app, it has been uploaded to *shinyapp.io*. A webpage from Shiny where developers can share their apps. For that end, the following link should be inserted into a web explorer: <https://sararo.shinyapps.io/LDOE/>.

For the laser application, the first subject to approach is the design of the webpage. The dashboard was created with *shinydashboard*, package that presents functions to divide the webpage into different areas. The present application divides the screen in two areas: a sidebar and a main panel.

The *sidebar* is the narrow-left navigation panel. In it all the different pages or tabs available in the webpage are shown. The sidebar has two main items: Project and Design of Experiments. This last subdivides into: Inputs, Outputs, Results and Plotting. It can be eliminated at any point by clicking on the top three horizontal lines, but it will be useful as long as it is the only way to navigate through the different items of the app.

On the other hand, the main panel is the great proportion left in the screen. Its content changes for every sidebar item and it shows an interactive interface where the user can insert and receive values or objects.

Followingly, all the different elements will be explained and matched with the expected interaction with the user.

Project

The project tab is merely formal and it connects the application with the thesis. It gives a brief introduction of what is the application designed for and gives credit to authors of both the application and the thesis.

Design of experiments

The content of DOE tab is a quick user manual. It focuses on the practical aspect of the application and explains, step by step, what should be done and what is expected to receive

from each page. Few theoretical information is given because the user is expected to be connoisseur of it when acceding the app.

The main panel divides in four different boxes, matching the subitems of DOE in the sidebar. Each box explains the basic steps to follow in each subitem. In this paper these steps will be addressed in the following subtitles.

Inputs

The inputs page is one of the most extensive due to the amount of information given and received. Five inputs are asked to the user and 3 outputs are given. The inputs are laser operation, input parameters, levels, number of runs and DOE method chosen.

As for the outputs, truly only two matrixes are returned: a full factorial design matrix and a fractional factorial design matrix. They are both shown for the user to check which one is more convenient. The selected matrix will appear again as the “chosen method matrix”, which will be the important one for the whole process.

All of the variables are followingly explained.

As for the inputs:

- **Laser operation.** As explained in section 3 there are different objective parameters for different laser operations. In this tab, there is a ‘radioButtons’ type of input that asks the user the type of laser operation he will study.

The code for this is:

```
radioButtons("laserop", "The laser operation is:", choices=c("Welding", "Cutting"))
```

Which fits the syntax of: *inputfunction("identificatory", "label with instructions that will be displayed", "options to show")*. Almost all shiny input functions fit a similar structure. This information is given to the reader in order to understand the basics of the code.

The desired functionality of this parameter is to save the type of operation. Later this information will affect the output tab. There will only be shown the output parameters variables compatible with the chosen option.

- **Input parameters.** The list of factors made in section 3 is shown to the user with a checkbox format. Through a list of ‘checkboxInput’ functions, the user should tick the input parameters he is interested in. Meaning not only that they are relevant for his study but also that he can easily change and measure them.
- **DOE parameters.** For the design of experiments some parameters should be indicated. They depend of the type of design we are studying.

For a full design, the *number of levels* for all of the factors was added with a ‘numericInput’ function. It is not studied for a fractional design because we are using a 2-level design. Which means the number of levels is already known, it is two.

Additionally, an input for the *number of runs* has been created for a fractional design. Full factorial design does not need this value because it can be calculated with the number of factors per the number of levels. The advantage of fractional design is that the number of runs lows, as it was explained in section 2, following the formula 2^{k-p} . With this input the user gives the difference of $k - p$.

During the development of the app, the first approach was to directly include the value of the number of runs, not this difference mentioned. The problem was the user must be aware

of this relation. If a random number was introduced, the possibilities of getting an error from the application were higher.

There is many more parameters but they were not included in the study. Coming next, code from CRAN is attached with the intentions of showing the magnitude of possible personalized variables. The functions of *fac.design()* from *DoE.base* and *FrF2()* from *FrF2* package are shown with some arguments to include. If those arguments are not included, they receive the shown default values. In italics are shown all the variables that were not contemplate.

```
fac.design(nlevels=NULL, nfactors=NULL, factor.names = NULL, replications=1, repeat.only = FALSE,
randomize=TRUE, seed=NULL, blocks=1, block.gen=NULL, block.name="Blocks", bbreps=replications,
wbreps=1, block.old.behavior=FALSE)
```

```
FrF2(nruns = NULL, nfactors = NULL, factor.names = if(!is.null(nfactors)) {if (nfactors <= 50)
Letters[1:nfactors] else paste("F", 1:nfactors, sep = "")} else NULL, default.levels = c(-1, 1), ncenter=0,
center.distribute=NULL, generators=NULL, design=NULL, resolution=NULL, select.catlg=catlg, estimable
=NULL, clear = TRUE, method="VF2", sort="natural", ignore.dom = !isTRUE(all.equal(blocks,1)), useV =
TRUE, firsthit=FALSE, res3 = FALSE, max.time = 60, perm.start=NULL, perms = NULL, MaxC2 = FALSE,
replications = 1, repeat.only = FALSE, randomize = TRUE, seed = NULL, alias.info = 2, blocks = 1, block.name
= "Blocks", block.old=FALSE, bbreps=replications, wbreps=1, alias.block.2fis = FALSE, hard = NULL,
check.hard=10, WPs=1,nfac.WP=0,WPfac=NULL, check.WPs = 10, ...)
```

Code is from the help guide of each package available in CRAN [37], [38]

In order to the system process all this information, an OK `actionButton` has been created. It should be pressed when the user has finished entering values. Then, the calculations will be done.

For that end, reactive values structures have been used in the server. They handle the interactive values given by the user. These are functions like `observeEvent` or `eventReactive`, followed with `(input, action)`. Whenever the input receives a value, the action will be done.

```
observeEvent(input$ok, {value$nr <- nofruns()})
```

Here is an example extracted from the app code. In this case when “ok” is introduced to the system (in this case means a button is clicked), the variable `value$nr` receives the result from the function `nofruns()`.

- **Method selection.** The left input, involving the selection of the DOE method, fits a similar programming syntax, using `selectInput()` function. Its objective is to save the desired method from the user, in order to save the correct matrix.

As for the outputs of this page:

- **Full Factorial Experiment matrix.** A matrix following the full factorial design is given. For that, the *DoE.base* package will be used, studied in section 4.1 and the function *fac.design* will be applied:

```
design1 <- fac.design(nlevels=input$nlevels,
                    nfactors=value$nf,
                    factor.names= reactive_text$inputs)
```

The inputs are the number of levels that the user already decided as an input. The number of factors is calculated through a function that adds the number of clicks in the inputs when pressing the “OK” button. And the factor names is a vector with the initials of the chosen inputs.

- **Fractional Factorial Experiment matrix.** Au contraire, the matrix given in this output is a fractional factorial matrix. For that, the *FrF2* package is applied, studied under the graphical package *RcmdrPlugin* in section 4.1 . The function used is also named *FrF2*:

```
design2 <- FrF2(nruns = 2^input$nruns,
              nfactors = value$nf,
              factor.names = reactive_text$text,
              default.levels = c(1, 2))
```

The first parameter is the number of runs, an input of this same page. And the number and name of factors will be the same as for the previous function. In this case, `default.levels` parameter was different from the default. For an average 2-level fractional design, the levels usually are (-1,+1). The levels were changed in order to assimilate levels between full and fractional matrix.

Responses

This page contains fewer information, and its objective is to decide which responses the user selects for the experiment. In the interface there are shown two outputs and between 2 inputs.

The first output is merely a reminder of what laser operation has been chosen. Laser operation input from the previous page is shown. For each value of operation, different response values are shown. For a laser cutting operation, the possible variables are, as said in section 3: Angularity and Perpendicularity and Edge roughness. For laser welding: Weld seam width and Hardness.

This is made by including an ‘if’ statement, or *conditionalPanel* for the shiny ui, every time the responses parameters must be shown. Inside the panel, if the condition is evaluated TRUE, a checking list of the appropriate responses is shown. Here there is an example:

```
box(conditionalPanel(condition="input.laserop=='Cutting'",
                    p("For laser cutting, the available outputs to study are:"),
                    checkboxInput(inputId="AP", label="Angularity and Perpendicularity"),
                    checkboxInput(inputId="ER", label="Edge roughness")),

    conditionalPanel(condition="input.laserop=='Welding'",
                    p("For laser welding, the available outputs to study are:"),
                    checkboxInput(inputId="WSW", label="Weld seam width"),
                    checkboxInput(inputId="H", label="Hardness")),
```

The user should choose what outputs is he interested in, in order to later measure it in the experiment.

Another update button has been created at this point. When the user fills the inputs, clicks the button. This action will make one last output appear. They are the initials of the chosen outputs. First for the user to know what is the code that will be used for its outputs and second for him to test that the code is properly running, and the values are properly updating.

Results

The results is a page that should be entered once the experiment has been done. There, the user should manually insert the results. Once the app has saved the inputs, number of runs, direct or indirectly, and outputs, the results page is ready to be used.

The first lines of the page are a reminder of the placed variables at that point. Once the user checks if the inserted numbers are correct, a *calculate* button should be pressed. This will generate an input matrix that the user is expected to fulfil. This matrix was created with the *shinyMatrix* package. Once again, the rows are the different runs of the experiment. So the columns are the different outputs that the user choose. This matrix will be saved for the following step with the *ok* button.

Plotting

In the last page, the plotting results are expected to be shown.

One plot is shown. It is the correlation plot made by *corrplot* package. The arguments of this function are the data frames created for the inputs with DOE and for the outputs by the user. In this plot, the inputs form the y-axis and the outputs the x-axis, which is in the upper part of the plot. Coloured circles fill the cells which relate rows and columns. The legend of the colours is in the right part. These circles give an overview of the relation between the variables. If the circle is big, so is the influence.

Additionally, a matrix with all the information plotted is shown for further doubts of the user.

At the end of the page, a linear regression model is applied to each response. Printing the summary of this model, offers statistic information very valuable. Among others, coefficients relating the variables are shown. In order to explain them, an example is given.

```
Call:
lm.default(formula = paste(G, "~."), data = dt)

Residuals:
  V1  V2  V3  V4
-0.25  0.25 -0.25  0.25

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)    2.75      1.09    2.524   0.24
FL             -0.50      0.50   -1.000   0.50
PV              -0.50      0.50   -1.000   0.50

Residual standard error: 0.5 on 1 degrees of freedom
Multiple R-squared:  0.6667,    Adjusted R-squared:  2.22e-16
F-statistic:    1 on 2 and 1 DF,  p-value: 0.5774
```

Figure 22: Example of `lm()` summary.

In **Figure 22**, two inputs (FL, PV) are related to one output (H, not visible in the screen selection). The attention should be put into the first column of the coefficients table. The first value is the independent value of the formula, and the followings are the coefficients that accompany the inputs.

In this case, the formula would be: $H = 2.75 - 0.5 * FL - 0.5 * PV$. It should be mention that this formula is the result of a random selection and does not necessarily fit the reality.

In order to generalize it, the formula could be: $output = Intercept\ coef \pm coef_i * input_i$, being i an index that matches the rows starting from the second one in the summary, which is the first input seen.

Coming to the end of the process, the user chose variables to generate a DOE matrix. With this experiments guide, the user was able to successfully make experimental runs where to get information. Now, this information is plotted and the user can see the relations between variables.

Further improvements.

As it was said before, this app is only covering basic aspects of both laser and DOE. Due to the lack of time and knowledge, some important aspects could not be covered in it. In this section some ideas for improvements are mentioned.

In general, more personalization and a bigger scope of the project is proposed as an improvement. Being able to study not only factorial designs but also response surface methodology could be a good point. So as increasing the plotting options for the analysis of results.

When developing the app, a *personalization of the levels* of the factors was thought. If the user is not familiar with the DOE, he could choose some values for each factor assembling the levels. There is a possibility to be able to change the levels with functions of the downloaded packages, avoiding the need of creating a function. In this case, the experiments matrix will directly be generated with the chosen levels. The ensurement of this affirmation will require a deeper study of DOE packages. This personalization of levels will not only help the unfamiliar user but also the plotting finish. For now, there are only levels plotted for factors, and this might hinder the view of the plot and its relations.

Additionally, some bugs appear with the actual app. At the beginning, when running the app, some *error messages* are placed on the screen because the functions do not have the desired values yet. An improvement could be to eliminate those messages. That could be done making the functions run for the first time only when ok button has already been clicked. This is not done due to lack of time.

Following the error messages line, the function FrF2() is not able to run any selection of variables. They should be chosen considering each other. For example, the number or runs cannot be bigger than the number of factors. When this happens, the application gives an error or either closes. A big improvement would be to prevent the application from stop and to generate popping messages that advert the user of the mistake.

Additionally, the app does not save the numbers for previous sessions. The line of time is composed of the user inserting data for getting the design matrix, going to the laboratory for the experiment and coming back to put the results. If the app closes at some point in the whole process, all the values will be deleted and whenever the app opens again, they should be inserted for a second time. Ideally, some sessions could be created for saving data. Or the app could enable an option to download and upload data.

6. My Shiny App: Manual

This is a manual for using the shiny app. Contrary to the previous section, this part does not require any knowledge on programming. All the steps for running the app are to be explained.

6.1. Running the app.

As mentioned before, the app has two running possibilities. One is through **the link of the shiny apps' webpage**. The other is through a program that supports R files.

The easiest way to run the app is with the link. If that is the case, the user can move to the next section, **Layout**.

If a R program is used, the following content is important for the correct start.

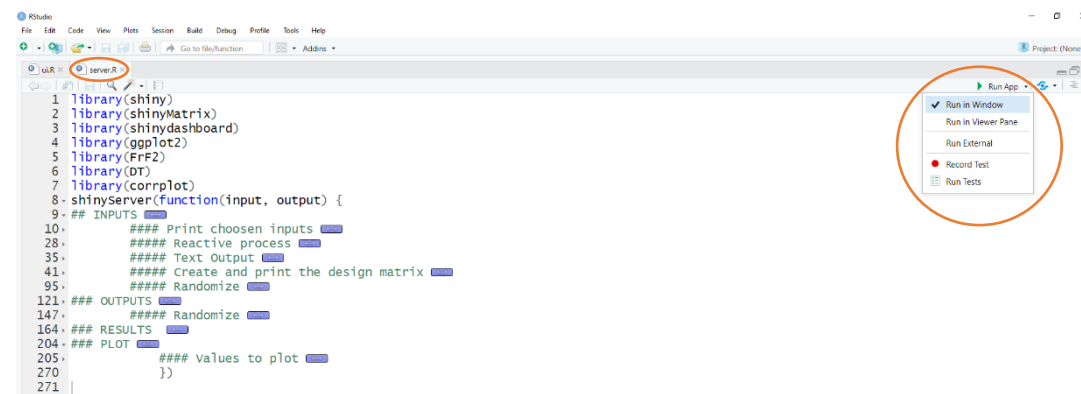
There are two files that contain the app. They are *ui* and *server*. In order to run the app, both should be opened with a R program. In this section RStudio is the program used.

Figure 24 and Figure 23 are attached to see the appearance. The name of each file appears in the upper left part. Regarding its content, both files have two parts. The first one is the loading of the libraries, which contain the functions needed. And the second part is the code, which is minimized in the figures. It can be seen by clicking in the small arrows of each line.



```
1 library(shiny)
2 library(shinyMatrix)
3 library(shinydashboard)
4 library(ggplot2)
5 library(FrF2)
6 library(DT)
7 library(stats)
8 shinyUI(
9   fluidPage(
10     dashboardPage(
11       dashboardHeader(title = "DOE for Laser Technology", titlewidth = 450),
12       ## SIDEBAR
13       ## DASHBOARD BODY (TABITEMS)
14       ### DOE
15       ### FACTORS
16       ##### Getting inputs from user
17       ##### RESPONSES
18       ##### RESULTS
19       ##### PLOT
```

Figure 24: File ui in RStudio.



```
1 library(shiny)
2 library(shinyMatrix)
3 library(shinydashboard)
4 library(ggplot2)
5 library(FrF2)
6 library(DT)
7 library(corrplot)
8 shinyServer(function(input, output) {
9   ## INPUTS
10    ##### Print chosen inputs
11    ##### Reactive process
12    ##### Text Output
13    ##### Create and print the design matrix
14    ##### Randomize
15    ##### OUTPUTS
16    ##### Randomize
17    ##### RESULTS
18    ##### PLOT
19    ##### values to plot
20  })
```

Figure 23: File server in RStudio.

The upper right part of both files has a button called *“Run App”*. It also has a dropping menu that enables to choose where the app is run. This menu is seen in Figure 23. If the *“Run App”* button is directly clicked, the default or last chosen option will be run. In this case it will be run

with “Window”. This means R studio will open a new window where the app will be shown. Nevertheless, if any other option is taken, the app will have a very similar view.

It should be mentioned this action can be made in any of the two files.

6.2. Layout

In this section the pages shown in the app and the steps to follow in each page are to be explained.

Firstly, the appearance of the pages is alluded. A familiar layout is chosen, which can be seen in Figure 25. Each page is divided in two parts.

The *sidebar*, on the left side, is a navigation menu. It guides the user through the different sections of the application. This bar remains identical for every page. An interesting feature is that the bar can be hidden by clicking in the three white horizontal lines. They appear in the upper part of the page, next to the title of the app.

The *main panel* is the remaining part of the page. In it, the different contents are updating for each tab.

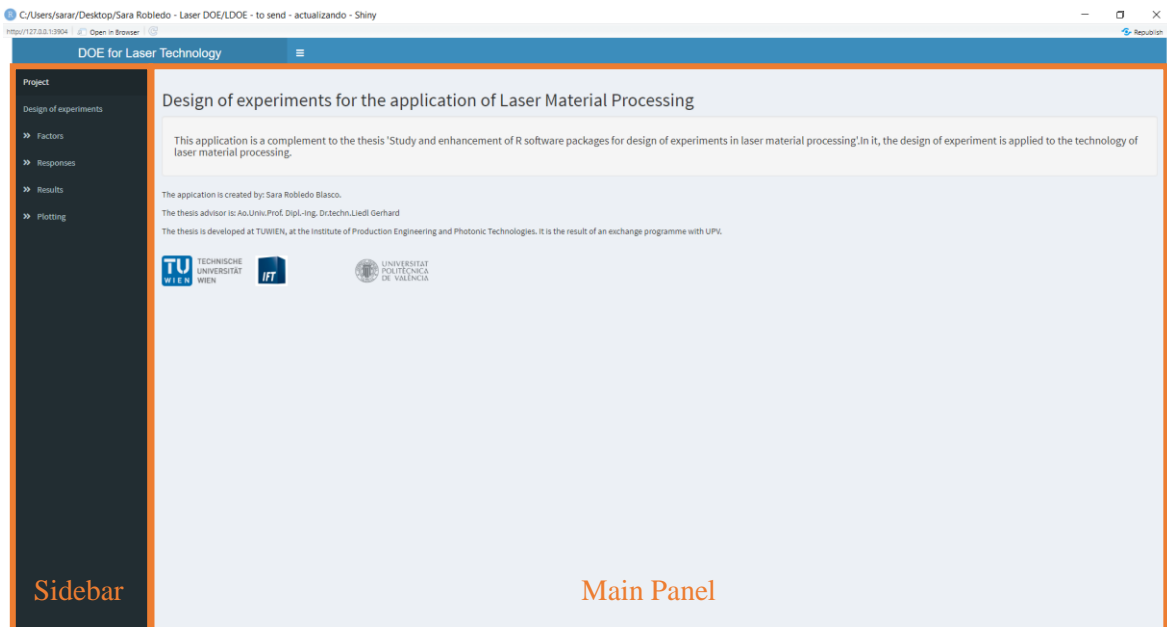


Figure 25: Project's tab.

The following sections will guide a route through the pages and procedure. It is important to respect the path given and avoid jumping sections.

6.2.1. Project

When opening the app, the first page that appears is the *Project*, already shown in Figure 25. In this page the app references the thesis, its author, supervisor and university. Its functionality is merely to create a link between the application and the thesis.

6.2.2. DOE

The following page is *Design Of Experiments*. In it the steps to use the app are shown. They are explained in the present document and briefly reminded in the application. This is due to the possibility of a user finding the application but not the thesis.

The Figure 26 shows the appearance of the page. Five boxes are shown, four of them regarding the following four tabs, and one regarding an additional feature: Random mode.

The first four boxes mainly explain the steps to follow, making emphasis on the clicking buttons to save the progress.

The last box explains the Random mode. It abides by each page having a clicking random button. By pressing it, a random selection of the values asked in that page is made. Its main functionality is testing the app. Nevertheless, it can additionally be used for exploring the Design Of Experiments.

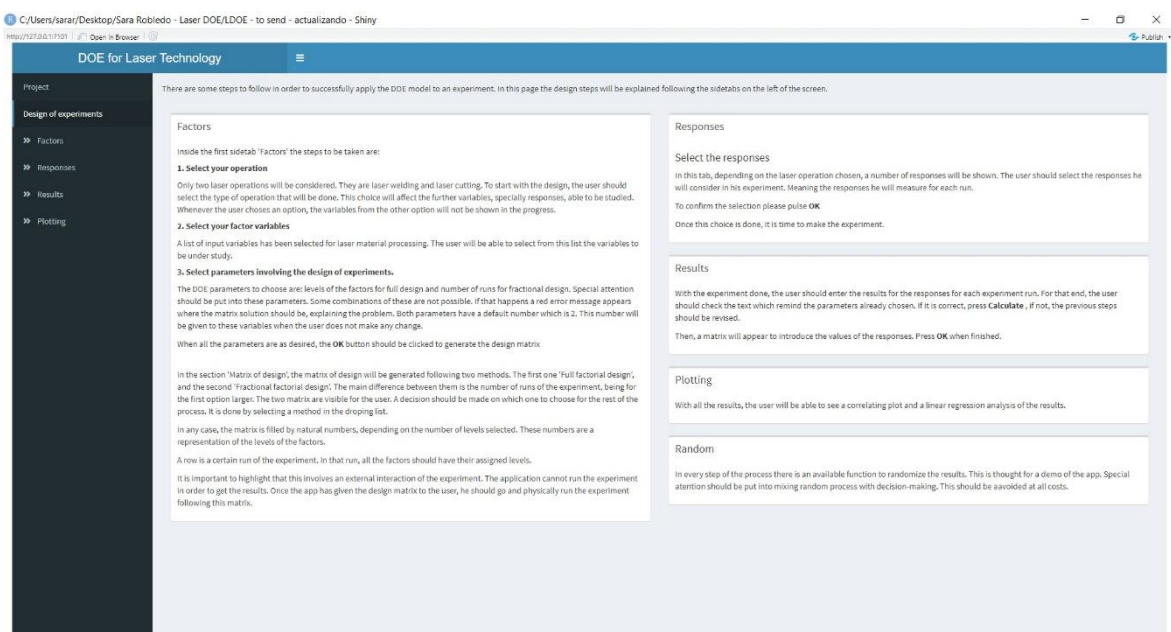


Figure 26: Design Of Experiments' tab.

6.2.3. Factors

The first interactive page is *Factors*. In this page, four inputs are asked in order to run the Design of Experiments.

They are: which **laser operation** will be used, a selection of **factors** or independent variables and two **DOE parameters** needed, such as the number of levels and the number of runs. As mentioned in the app page, the DOE parameters do not affect the both methods. The number of levels only affects full factorial designs. And the number of runs only affects fractional designs. The reason is explained in section 5 of the present document.

All four inputs can be seen in **Figure 27**. They are included in the blue and white upper boxes. When these inputs are introduced, the **OK** button should be press in order to save the data. This button is emphasized with an orange circle in **Figure 28**.

In **Figure 28** the resulting matrices of full and fractional designs appear in the lower tabs of the page, named after its methods. The user should observe both matrices and decide which

method will be used. This will be decided by selecting it in the dropping method list above the matrices. The selected matrix will be saved and shown again in the third tab, named “Chosen method matrix”.

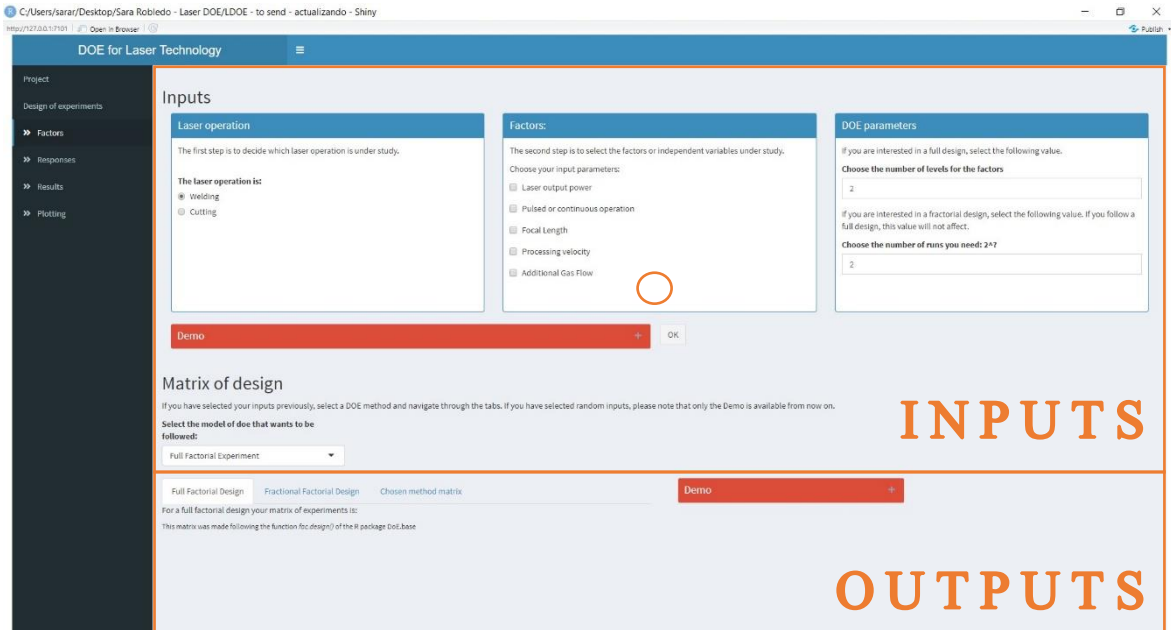


Figure 27: Outputs' tab.

Noticeable to the sight, two red boxes called “Demo” appear in the page. One under the input’s boxes, and the second next to the matrices. By clicking in the adding symbol, a box drops and a “Random” button is available.

In the first box, by clicking in the button, a sentence with the randomized values appears. In this case the “OK” button should not be clicked. Then the user inputs will be saved instead.

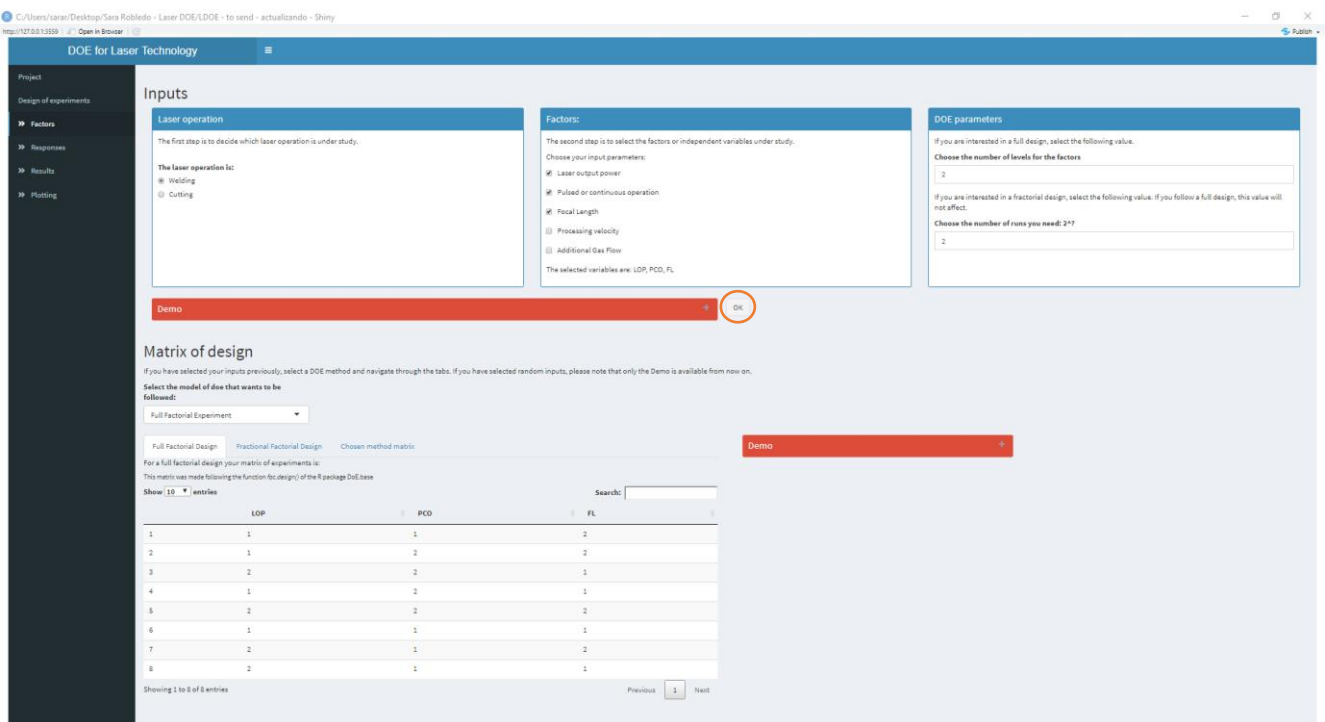


Figure 28: Outputs' tab. Results.

If this step is made, the second box button can be clicked. Inner the box, a matrix from a random method will appear.

6.2.4. Responses

The following page is *Responses*. Its main function is to select the response variables. **Figure 29** is referred as the page layout. Nevertheless, two actions are taken.

Firstly, the application *reminds* which laser operation was chosen in the previous page. Depending on this variable, different responses are shown. It appears in the yellow left box.

Secondly, the user should select the *responses* to use in the study. Two options appear for each type of operation. This action occurs in the middle blue and white box. Again, when selected the variables, the “OK” button should be pressed to save the data.

A third box appears in the right. It is the demo box. With a similar procedure to the previous, a button appears when clicking the adding symbol. This button makes a random selection of the available responses.

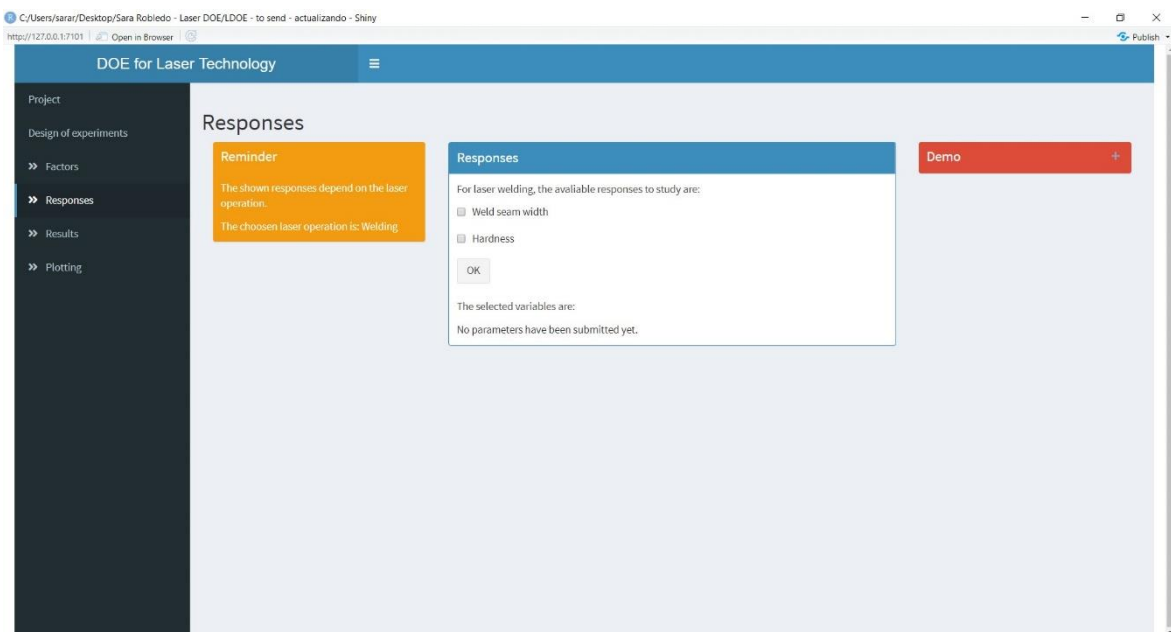


Figure 29: Responses' tab.

At this point, the user has all the information needed to make the DOE experiment. He should go and run it, and then come back to the app with all the measures.

6.2.5. Results

The *Results* page collects the experiment measures for further plotting in the next tab. It fits similar functions to *Responses* page but has a different appearance. This page can be seen in **Figure 30**.

The first part is the *reminder*. In this case is the text positioned in the upper part of the page. It is fulfilled with the obtained values in previous pages and connects them to the results of the experiment, followingly asked. For a better understanding an example is presented: the number of runs will be the number of rows asked in the measurements. This parameter was determined in **Factors**. It will be reminded in the text because it is crucial to shape the measurement matrix.

The user should check this information and press “Calculate” if agreed. If this information is not correct, the previous steps should be checked.

When the button is pressed, a matrix appears fitting the specified characteristics of the previous text. The columns fits the response variables and the columns, as it was said, the number of runs. The matrix should be filled with the measurements and the button “OK” should be pressed when finished. In **Figure 31** a filled matrix is shown.

Once the data is saved, the user can move to the next page.

Again, a demo box is shown for a random selection of the results.

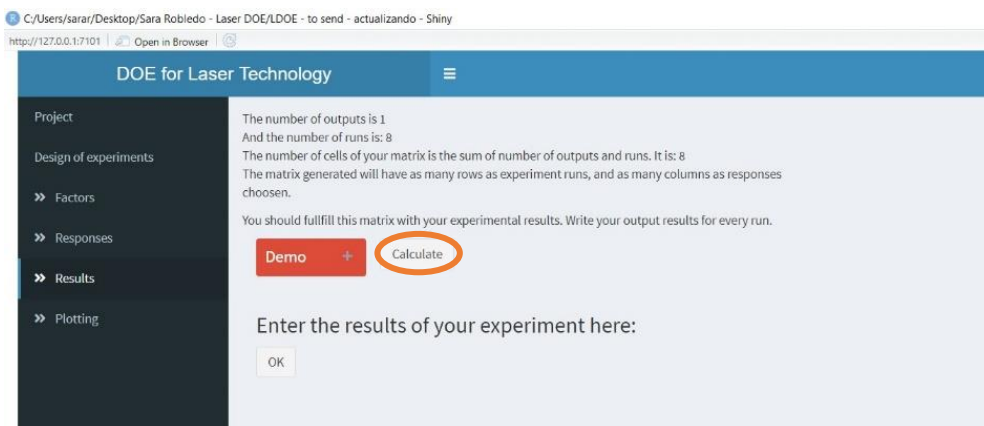


Figure 30: Results' tab.

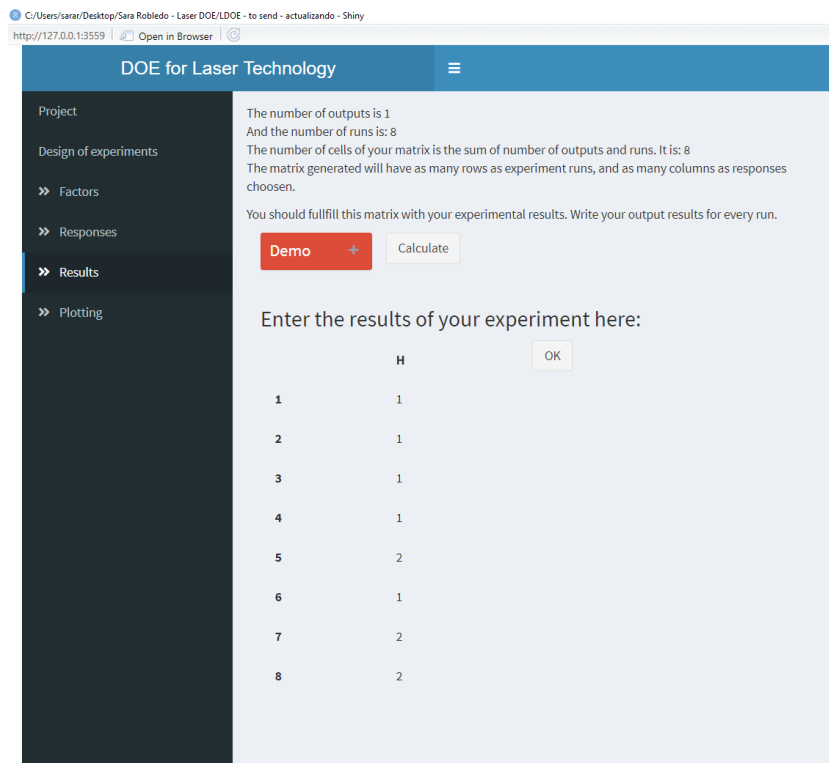


Figure 31: Results' tab. Responses matrix.

6.2.6. Plotting

The last page is *Plotting*, where all the information is plotted and analysed.

If the method followed through the process has been introducing the variables, any action should be done and the plot and analysis will directly appear.

On the other hand, if the process has been done through randomization, its box should be unfolded and its button click in order to see the results.

In both cases, the result is the same. A correlation plot and a lineal regression analysis.

The **correlation plot (Figure 32)** appears in the upper part of the page, and it relates the factors (y-axis) with the responses (x-axis) via coloured circles. The color legend appears in the right of the plot. Additionally, the matrix used for the plot appears right down.

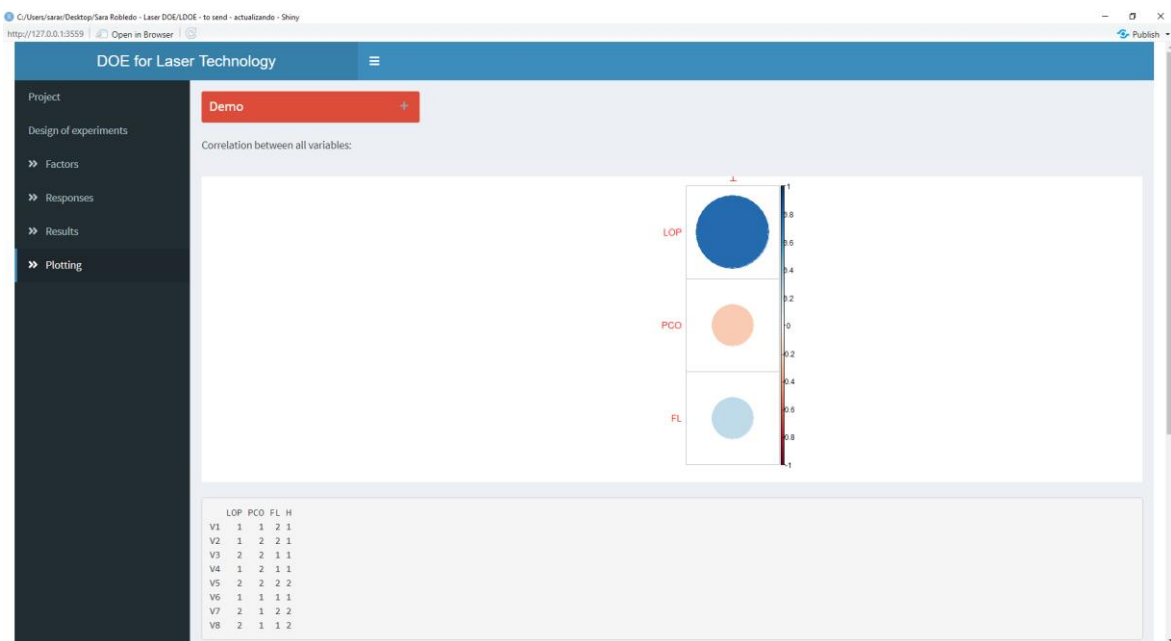


Figure 32: Plotting's tab. Correlation plot.

The **linear regression model (Figure 33)** is positioned down the plot and matrix, and it is fully visible scrolling down the page.

The first element is the code for calling the *formula*. It gives no information to the user.

The second element is a vector with the *residuals* of each run. The residual measures the difference between the real value and the prediction. They will give information if a deep statistical analysis is wanted.

The third element is the *coefficient* table. The main reason for printing out the analysis. A formula relating the variables can be obtained from this table. The procedure is explained in the section **Web Application..** More statistical variables are offered following the table. This study will not deep in them, but they are very useful for statisticians to know how good the results are.

```
Call:
lm.default(formula = paste(G, "--"), data = dt)

Residuals:
      V1      V2      V3      V4      V5      V6      V7      V8
-2.500e-01  2.220e-16 -5.000e-01  2.500e-01  2.500e-01  4.025e-16  3.886e-16  2.500e-01

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.2500     0.6614   0.378  0.7247
LOP          0.7500     0.2500   3.000  0.0399 *
PCO         -0.2500     0.2500  -1.000  0.3739
FL           0.2500     0.2500   1.000  0.3739
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.3536 on 4 degrees of freedom
Multiple R-squared:  0.7333,    Adjusted R-squared:  0.5333
F-statistic: 3.667 on 3 and 4 DF,  p-value: 0.1208
```

Figure 33: Plotting tab. Linear regression analysis.

7. Conclusion.

In this thesis three science areas were connected: statistics, laser technology and programming.

The statistics area was studied through the *Design of Experiments*, a tool that helps the planification of experiments in a time effective manner. Already knowing what the aim of the study was, many methods were investigated. *Factorial design* was finally chosen due to its ability to show variable dependencies.

For any DOE method, input and output variables should be determined, referred as *factors* and *responses* respectively. With the implementation of a guided experiment, the results are obtained, plot and analysed.

The parameters were specified for *laser material processing*, more specifically, laser cutting and laser welding. They were examined counting on inputs (factors in DOE) or outputs (responses).

The *inputs* examined were laser output power, pulsed or continuous operation, focal length, processing velocity, additional gas flow, wavelength, focal position and area of the laser beam in the workpiece surface. From this list, the first five were considered important for the experiment.

As for the *outputs*, they needed to be specified for each laser operation. For laser cutting were studied angularity and perpendicularity, edge roughness, drag, melting on top edge and dross. Making a final selection of the first two. For laser welding an initial list formed by weld seam geometry, hardness, area of pores and joint strength was also reduced to the first two.

The procedure used for applying the DOE to laser was via *R programming*. The first step was to study the R packages available for DOE analysis. With many packages accessible, the final choice was to select *DoE.base* and *FrF2* for the development of an application. The app was coded in RStudio, using R language and many libraries, between which *shiny* is stood out.

The result of this thesis is an application to study DOE and laser technology freely available. The parameters to study can be chosen and analysed with correlation and linear regression. The ultimate achievement is to obtain coefficients that relate the laser variables.

With this application, time and cost saving is expected when experimenting, so as a basic knowledge of the relation of laser variables.

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