POLITECNICO DI TORINO

Master degree course in
Mechatronic Engineering

Master Degree Thesis

Experimental characterization of the removal torque of PET bottles as a function of capping conditions

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Chapter 1

Introduction

1.1 Background

The use of packages to transport and preserve food and drinks has been known for thousands of years. Around the late 1970s, plastic has been introduced as a new packaging material replacing paper or glass products in many of their uses [1].

The wide diffusion of plastic bottles might be attributed both to their mechanical properties and to the great design freedom that the material gives, which surely makes the products more appealing. In the past, the design process has been mainly focused on manufacturing packages that preserve the goods they contain, especially with the use of tight seals that often result in hard-to-open bottles. On the other hand, in recent years the trend shifted towards a more customer-centred design. In other words, the modern focus is an eye catching and easy-to-use product that also serves well its main purpose [2].

As of 2017, some studies estimate a yearly consumption of around 46 billion single-use PET beverage bottles in Europe [3]. Among the users population there are many kids, elderly people and people with disability for whom opening a tightly sealed bottle is not just an inconvenience, but it can become challenging; hence the increasing interest of beverage companies in offering an easy-to-open product.

For most beverage containers, this requirement of accessibility along with the packaging specifications needed to ensure the preservation of the drink itself, are translated in the determination of a desired removal-torque interval. This means that the torque necessary to open a bottle has to remain within a specific range. If it is too modest the beverage is not well preserved whereas, if it is excessive, the content of the bottle is not easily accessible.

It is evident that the problem of guaranteeing an appropriate removal-torque is not restricted to the beverage industry; all the capped containers may be subject to this requirement. Therefore it is crucial to correlate the variables involved in the capping process with the resulting removal-torque to be able to offer a product with the desired characteristics.

Currently there is no standard procedure to characterize the behaviour of the cap-bottle coupling. Most companies rely on acceptance sampling (also called sampling inspection), which means that samples of the product are tested after the capping process. If the results from this statistical analysis don't comply with the specifications, the capping machine has to be recalibrated and, in the worst case, an entire lot could be rejected.

Figure 1.1: A preform and its capsule.

The idea behind this thesis work is to obtain a mapping of the bottles' removal torque as a function of the capping conditions. The purpose of this study is demonstrating a procedure to find the best capping conditions so that, in the near future, it will be possible to predictively correct the process obtaining optimal results. For example, if a variation of the caps temperature is detected, an appropriate correction can be made on-line without the intervention of an operator.

1.2 AROL

The tesis work has been carried out in the **AROL** company, founded in 1973 by Bruno **Ar**iano and Franco **Ol**ivieri. It was born as a company manufacturing capping machines mainly for wine and liquor bottles, but since 1978 it started to expand its business under the guidance of its new partner Sergio Cirio; the closure systems wouldn't be dedicated to just wine and liquors anymore. 1983 can be identified as the beginning of the modern AROL because, in conjunction with the diffusion of PET bottles, the company started to expand its market to new sectors dedicated to the packaging of liquids.

This revolutionary application of plastic containers pushed the company to research and develop new solutions, still in the capping field, but directed at a bigger range of customers which was going to grow exponentially with time.
In the following years AROL merged with smaller but specialized companies, helping

it to become a world leader in the market of closure systems. For example, in 1995 the company merged with CLOSYS that is specialized in small single-headed cappers like the one shown in figure 1.2 which feature production rates of 2500 ÷ 3000 bottles per hour (BPH). Although these machines are relatively small, they still cover a large share of market.

Figure 1.2: A CLOSYS single head capper.

It is partly thanks to these types of mergers that AROL has installed about 16000 machines around the world and continues to produce some 700 machines every year. Another reason is the production of different types of machines.
In particular, there are *stand alone* machines which work synchronously in a production line with other systems and are essentially part of a plant. Consequently, AROL must deeply cooperate with other companies as early as the design stage.
Another type is that of *free standing* machines, working in an autonomous way. They use their own power supply and have a separate working area. Although this type of machine is still mounted in the production line of a plant, they don't work synchronously with other machines. Conveyor belts are used to move the containers to cap, while the machines are equipped with mechanical systems able to align them to the capping elements.
As mentioned before, AROL collaborates with other companies of the sector. For example, this is the case of SIDEL, which manages entire bottling lines from PET bottle blowers to labelling systems for many beverage, food, chemical and cosmetics products.
AROL is the exclusive SIDEL supplier for project collaborations. This continuously pushes the company towards innovation and improvement of its products to keep them up with the technological development of the production lines and the systems they are integrated with.

1.3 Structure of the thesis

Chapter 2 starts with a brief summary of the working principle of capping machines which is useful for a better understanding of the removal-torque mapping station structure. Chapter 3 is dedicated to the description of Lab V, which is the name given to the measuring system used. The variables of interest that make up the collected data are analysed in 4, which goes on explaining the testing procedure more thoroughly. Chapter 5 is dedicated to data manipulation and describes the logic underlying the scripts that have been developed for this purpose. Lastly chapter 6 focuses on the results obtained from the tests and suggest possible future developments for this project.

Chapter 2

Capping principles

First of all it is important to understand the working principle of a capping machine since the measuring system has to replicate the real sealing process as closely as possible. Although there are different capper models commercially available, the working principle described below is related to a carousel-like capping machine (Figure 2.1) since it is the same used as a reference for the present measuring system.

Figure 2.1: A rotary capping machine.

A capping machine is a complex assembly of many parts but, in order to understand its working principle, it is sufficient to consider the sub-systems indicated in figure 2.2:

- Carousel
- Capping axis

- Cap delivery system
- Conveyor system for the bottles

Figure 2.2: Close-ups of a rotary capping machine.

The Carousel is the bulkiest part of the machine. It rotates around a vertical axis with an angular velocity that depends on the plant production speed. The capping axes, also called capping turrets, are mounted on the carousel periphery. They are arranged at an equal angular distance from each other and can both translate vertically and rotate around their symmetry axis. Therefore the capping head motion is obtained from the composition of two rotations around vertical axes and a vertical translation.

The translation of the capping head is governed by a cam profile which may be different for each machine model. A carousel with n turrets can close n bottles per revolution, thus the machine production rate can be obtained multiplying n by the carousel rotational speed; Modern capping machines (e.g. AROL Euro PK) can produce up to 1500 bottles per minute (90,000 BPH).

Each capping head follows the same trajectory, hence describing the action of one is enough for the purpose of this section.

The bottles travel through the plant on a conveyor belt. The machine is equipped with a system that takes the bottles from the conveyor and arranges them on a rotating carrier which keeps the alignment between the bottle necks and the turrets.

In another section of the machine, caps are delivered on a rotating disk that serves the purpose of phasing the capsules with the bottles and the turrets; an approaching capping head starts to descend, grasps a cap and rises up again. Every turret has a cone on its end which is designed to grab and transport the caps without dropping them. After a well determined angle the capping head will again move down, this time to apply the cap on a bottle. During the whole process the turret spins around its axis. Since the carousel and the capping heads are geared together through an epicyclic gear train, the rotational speed of the two are related by a machine-specific gear ratio.

During its vertical descent on the bottle, the capping head has to exert a force. To begin with, the capsule seal (see figure 2.3.) has to be pushed over the bottle thread then, when the cap ceiling touches the sealing surface on the bottle (refer to figure 2.4) it's necessary to have a closure force. This pressure is needed to avoid slippage while the closing torque is applied, so the bottom side of the neck ring is pushed against some small pins that penetrate into the plastic and keep the bottle in place.

Figure 2.3: Seal of a PET cap.

The closing torque is held constant for a pre-set amount of time called time-in-torque after which the capping head rises and the closed bottle is fed back to the plant conveyor belt. Time-in-torque is one of the many parameters that influence the resulting opening torque of a bottle. It's clear that the choice of this value is limited; in fact it has a maximum value since the closure has to be completed within a well defined arch of the capping machine.

In many cases, the thread used on PET caps and bottles has just one start, hence in the worst case scenario the beginning of the thread on a cap touches the thread on the bottle finish just after its origin. In this case the capping operation lasts one turn of the turret more than the minimum turns required to screw the cap. The maximum value of the time-in-torque is computed based on this situation.

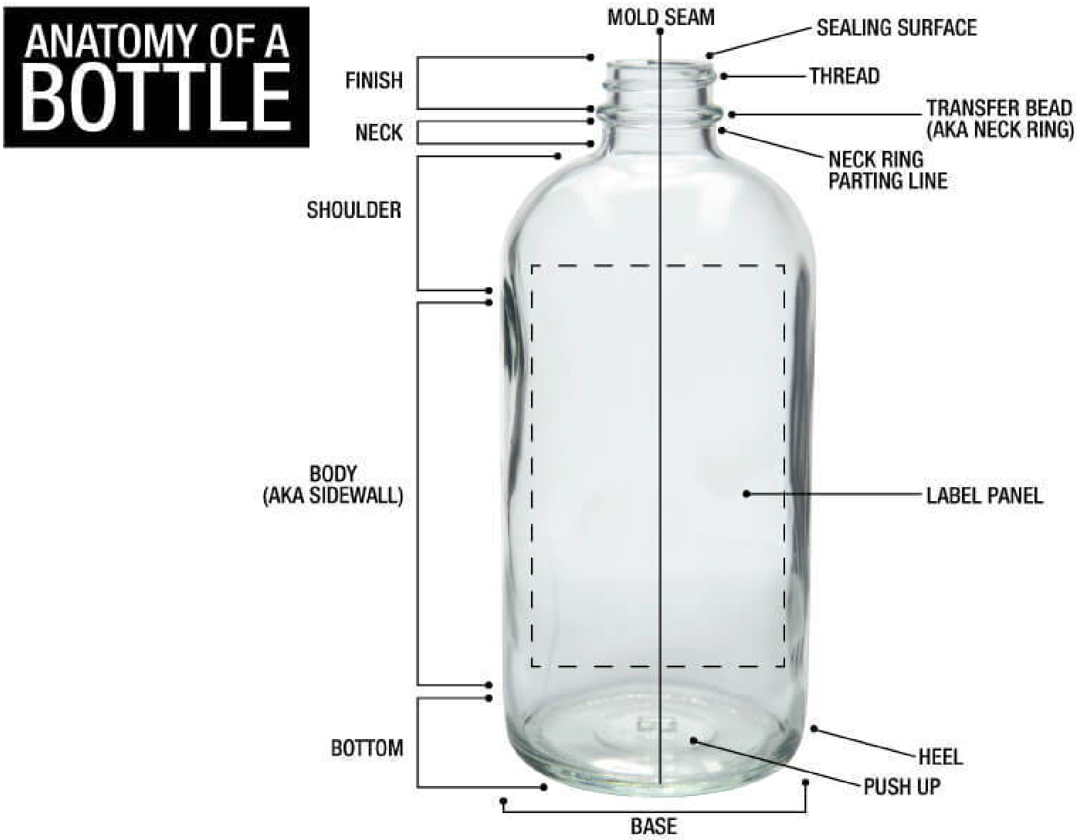


Figure 2.4: Anatomy of a bottle.

Chapter 3

Lab V

The tests are performed on preforms like the one shown in figure 1.1 and are needed to characterize the influence that various parameters have on the capping process. Consequently it is necessary to replicate the crucial steps that a capping machine normally carries out to obtain meaningful results.

3.1 Structure of the testing machine

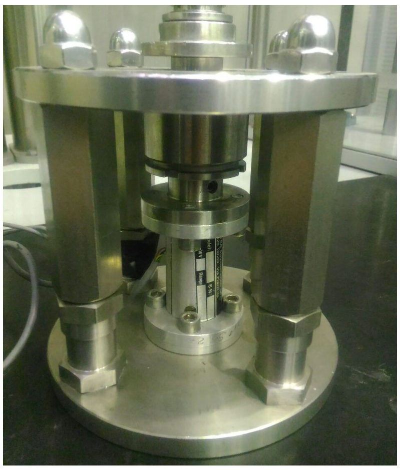
The structure of the lab V resembles that of a carousel-type capping machine. Since this apparatus has been designed to perform one closure at-a-time, it has just a turret which does not rotate around the carousel axis. Likewise, there is no need for a cap dispensing system because a capsule is manually loaded in the turret's cone before every test. Obviously, the bottle is also stationary and is constrained under the capping head. Lastly, there is not a mechanical cam profile; the cam parameters are contained in a file that is loaded into the machine memory through the HMI and the turret vertical displacement is controlled electronically. Such a solution allows to test various capping conditions just editing the cam file without having to physically mount it.

Although the listed differences may seem substantial, they shouldn't affect the results which are mainly influenced by the cap-bottle interaction. As a matter of fact, the relative motion between the bottle and the capsule is left unchanged, hence the results obtained should be a good representation of the real capping process.

The machine is equipped with a system to position the preform and maintain it still during the cap application. This system is connected to the basement through a torque meter that can be used to measure the torque applied to the bottle during the capping phase (figure 3.1).

In addition to that, another machine is used to measure the removal torque. It is also equipped with a system to lock the capped preform in place and a torque meter that records the signal of the opening torque with the option of saving it on a csv file.
The removal torque characteristics has an increasing trend up to a maximum, after which it drops to zero. The value of interest taken from this measurement is the peak, as it is what the end-user perceives when opening a bottle. The instrument used also indicates this value on its display.

(a)



(b)

Figure 3.1: The preform locking system (a) and the torque meter (b).

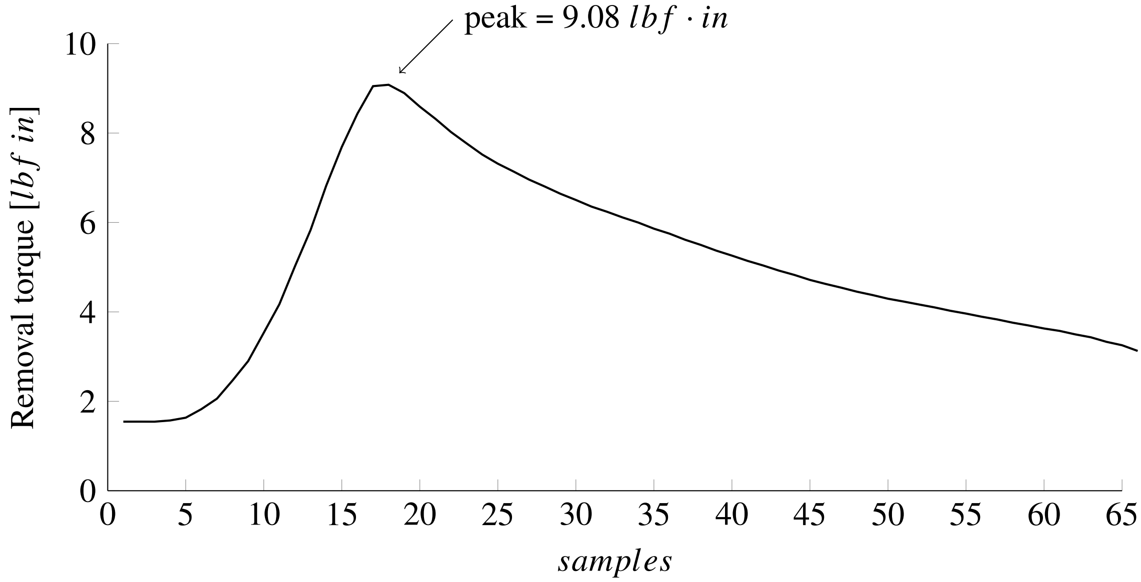


Figure 3.2: Example of removal torque characteristic.

Chapter 4

Data collection

As mentioned in the introduction, the objective of this thesis is to map the removal torque of PET capsules as a function of different capping conditions. The first section of this chapter will illustrate the most important parameters influencing the capping process and how they have been controlled for the tests. The following section will then explain the tests performed and the procedure used to gather the data.

4.1 Parameters of interest

The company which sponsored this work, has carried out some tests to identify how many parameters influence the results of the capping process. The total number of variables found is about 96 but, for simplicity, this activity has been performed only considering few of the identified parameters. The choice has fallen on the following five variables:

- Closing torque
- Time-in-torque
- Capping speed
- Capsule temperature
- Settling time

A first testing campaign has been performed to figure out the influence of time-in-torque, temperature and settling time as requested by a customer. Based on the results from this analysis, a second campaign has also included the other parameters.

Closing torque

This is intuitively the most influential parameter of all. During the capping process, a specific torque is applied to the capsule which, under this solicitation, will slightly deform to adapt itself to the bottle finish. It is very difficult to model the behaviour of plastic materials, therefore it is simpler to observe that the opening torque will increase with the applied closing torque, remaining always somewhat smaller.

The testing machine uses a brushless motor to spin the capping head. The closing torque is set on the machine HMI and this information will be used by the controller to generate a current limit. This will be used as a saturation value for the motor during the capping process.

Time-in-torque

Time-in-torque refers to the time interval during which the closing torque is held constant. Currently, AROL capping machines hold the torque for around $80 \div 100ms$. This variability is due to the uncertainty of the bottle-cap thread coupling. As explained in chapter 2, in the worst case scenario, the capping head makes one additional turn which translates to a longer capping phase that, in any case, has to be completed within a specific machine angle.

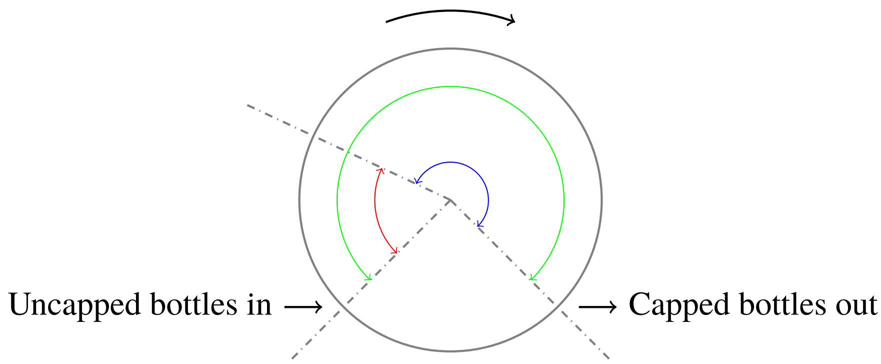


Figure 4.1: The maximum angle reserved for the capping phase (green), the uncertainty due to the misalignment of threads (red) and the effective minimum angle needed for the capping phase (blue).

The testing machine uses an electrically controlled capping head, meaning that its vertical displacement does not rely on a physical cam profile, instead the head is moved by a motor. The reference signal is again generated by a controller that interprets a cam profile set on the HMI (see figure 4.5). This system allows to test the effect of various time-in-torque values without having to manufacture the physical cam profile. It's evident that choosing a time-in-torque larger than $100ms$ for the actual bottle capper, would require a redesign of the entire capping machine.

Capping speed

It has been observed that the speed at which the cap is applied, greatly influences the removal torque. The material of the cap deforms differently depending on the application speed and for this reason the opening torque is affected.

The testing machine simulates an industrial bottle capper, consequently it is possible to select the desired plant production speed and the transmission ratio of the machine to simulate. With these two parameters the capping speed is determined and controlled. To spin the capping axis, a brushless motor with integrated drive is used. A speed control loop maintains the cone rotational speed constant until the last phase of the capping process where the torque exerted on the bottle reaches its set maximum value; the controller therefore limits the current drawn by the motor that consequently slows down to a stop.

Capsule temperature

The plastic caps, subject to the same solicitations, show a different behaviour when their temperature is altered. Currently, in most bottling plants, there is no system used to control the capsules' temperature. Those are usually stored in warehouses which are rarely air-conditioned, therefore the caps arrive at the capping machine with a highly variable temperature. Understanding the effect of temperature on the opening torque will help to evaluate whether or not it is convenient to arrange a system controlling this parameter before the capping process to achieve a more repeatable opening torque.

Varying the temperature of the caps is achieved through a small climatic chamber. Also, before each test, a cap is selected and a check with an infrared thermometer is performed. When the cap is at the chosen temperature for the test, it is placed under the capping head and the test is initiated.

Settling time

This parameter refers to the time between the closure and the opening of the bottle. Usually, for quality control purposes, the bottles samples to be tested are withdrawn from the production line just downstream of the capping machine. Therefore the opening torque is measured almost immediately after the closure. On the other hand, customers will experience a different torque since the bottles will be opened many days after the manufacturing process.

The main specification for this study, is the opening torque as sensed by the customer. The closed bottles are stored for different time intervals before being tested. It is expected that after a certain amount of time the opening torque value will settle. Testing this parameter was necessary to establish a convenient time interval for the opening test; not too short to let the opening torque value settle, but not too long either to avoid wasting time.

4.2 Testing campaign #1

As mentioned in section 4.1, these first tests will serve the purpose of understanding the effect of time-in-torque, temperature and settling time on the opening torque. As a consequence the other parameters (closing torque and capping speed) remained constant.

Design data

The capsule type used for the tests is called VR-28/1881 and the preform is a compatible model.
According to the manufacturer, the VR-28/1881 is in production since 2012, it features a 28 *mm* - 1 start thread for bottles with a PCO-1881 neck finish, like the preform used. The main features of this cap are reliability of the closure and convenience due to its reduced weight. This type of cap is a development of the older models made for the 1810 neck finish which were taller, heavier and consequently more expensive [4].

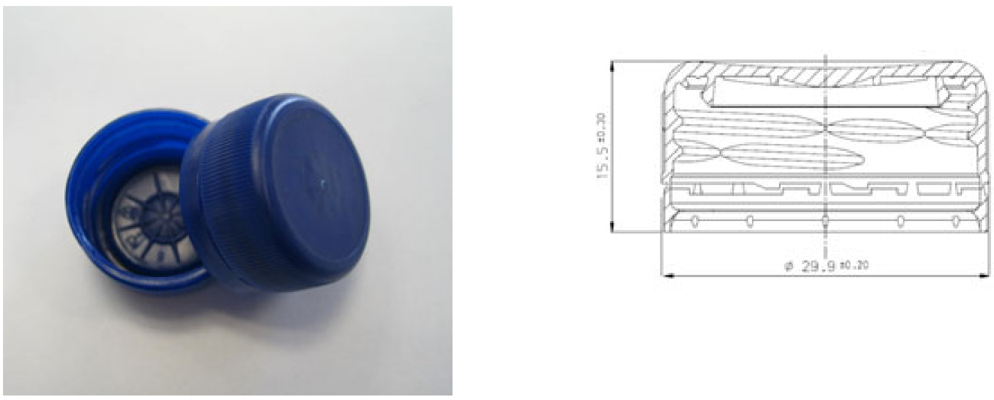


Figure 4.2: The capsule used for the tests. [4]

The torque set for the tests is 1.81 Nm (16 $lbf \cdot in$). This value is chosen based on the specifications provided by the customer who requested this study. The same specifications indicated a desired vertical load of 245.25 N (25 kgf) and a capping temperature above 10 ^oC.

Figure 4.3: The preform used.

With this setup, the influence of three parameters has been evaluated:

- Time-in-torque: with values in the range $0 \div 500$ ms
- Capsule temperature: with values in the range $10 \div 50$ ^oC
- Settling time: in the range $0 \div 24$ h

For this test campaign, time-in-torque, capping temperature and settling time assumed respectively 7, 5 and 3 values. Each combination of these is referred to as "capping state", so in this case 105 states have been analysed.
For every one of the capping states, 7 preforms have been closed and reopened to obtain meaningful data set. Consequently the total amount of test cycles is 735.

A summary of the design data is shown in table 4.1.

Editing the cam profile

In this section it is explained how it has been possible to achieve the different time-in-torque values.

Parameter	Value						
Cap	VR-28/1881						
Preform	PCO-1881						
Cam profile	Custom						
Capping head	Equatorque						
Capping torque $[N \cdot m]$	1.81						
Top-load $[kg]$	25						
Closures for each test	7						
Time in torque $[ms]$	0	50	100	200	300	400	500
Capping temperature $[^oC]$	10	20	30	40	50		
Settling time $[h]$	0	24	48				

Table 4.1: Summary of the design parameters for the first test

As previously mentioned in section 4.1, the time-in-torque is varied thanks to an electrically controlled capping axis called 'equatorque'. The axis rotates and translates thanks to two motors:
one brushless motor controls the capping speed, while the other is a linear actuator connected to the capping axis to control its vertical displacement.
The HMI communicates with the motors controllers, hence it is possible to set the desired motion profile of the capping axis cone just by adjusting some parameters on a specific menu. In particular, through these adjustments, it is possible to set a custom cam profile as the one shown in figure 4.4. During the test cycle, the machine will simulate the operation of one head of an hypothetical rotating capper on which a cam with the custom profile is installed.
The image shows a linearised parameterized cam profile. The horizontal axis shows the angle with respect to the capping machine rotation axis. As already explained before, this particular testing machine doesn't spin around the main axis but only around the capping axis, therefore the indication of the abscissa is only 'virtual' although it can be also read as time, since time is proportional to the indicated angle. The vertical quotations are measurements of the capping head displacement in *mm* which is conventionally 0 in the highest point of the profile. The fixed values of the cam profile are blurred because they are considered confidential material.

In a capping machine, the different stages follow each other in this fashion:

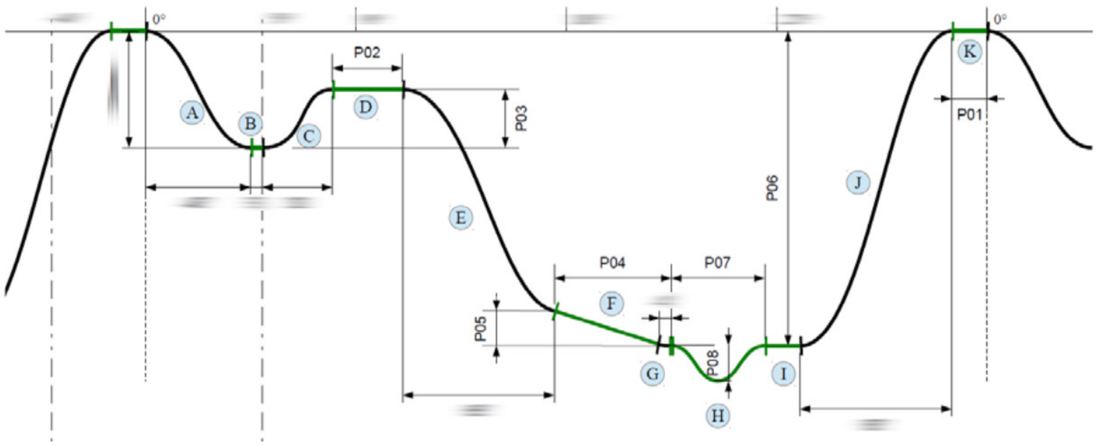


Figure 4.4: Main parameterized cam profile.

0° The starting point of the profile at 0^o, is at a specific angular distance before the cap delivery disk.

A The capping head descends towards the said disk.

B A cap is taken and retained by the cone at the end of the head.

C The capping head rises of $P03$ mm to avoid unwanted contact with the cap delivery disk.

D The cone stays at this height until it has passed the disk, that is for an angle $P02$.

E Is the phase in which the cone approaches the bottle.

F Here the effective capping phase begins with the capsule being screwed on the bottle thread.

G-I Usually, phases G through I are represented as an horizontal line during which the closing torque is kept constant.

H This phase is used only in the so-called 'accessory cams' which are not relevant for the scope of this thesis. In our case $P06$ (H) was set to 0.

J The capping head rises again after completing the closure.

K The cone stays at its highest point for $P01$ degrees, after which the cycle is completed.

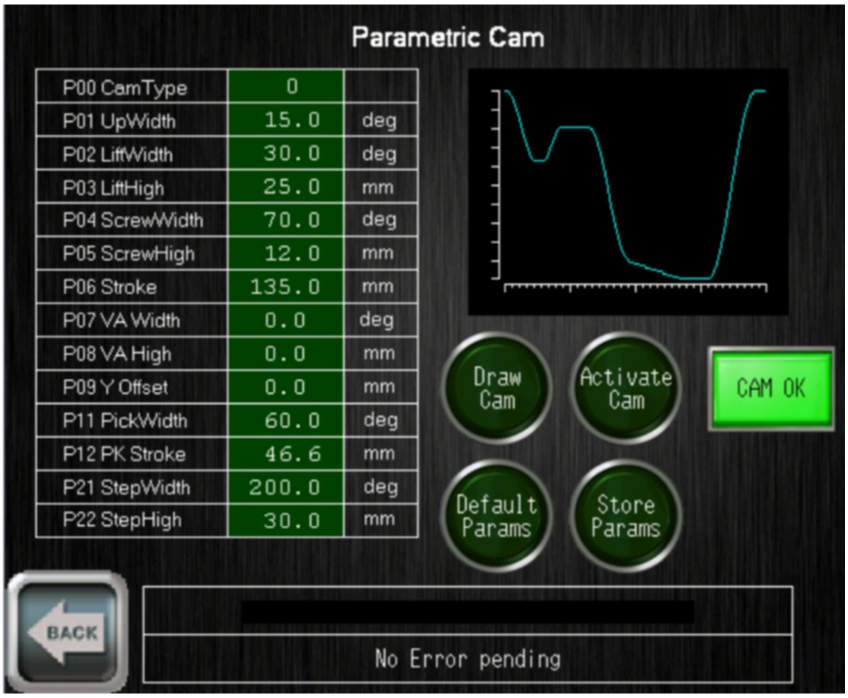


Figure 4.5: The HMI page to set the custom cam profile.

From this profile, both parameters *P*07 and *P*08 are set to 0 while it is possible to vary the length of phase I, hence the time-in-torque, changing the values of *P*01, *P*02 and *P*04.

Picture 4.5 shows the page of the HMI dedicated to setting the cam parameters.

In the picture is also possible to see other parameters (*P*09 through *P*22) which currently are just ignored but are left in the panel for eventual future developments.

Varying temperature and settling time

The temperature has been controlled using a climatic chamber, while the different settling time values have been achieved storing the closed preforms for the chosen amount of time.
To avoid confusion, every closed preform had its state written on it with a permanent marker, along with the number of the measurement from 1 to 7.
Furthermore, every 7 preforms of each state have been grouped together in sealed plastic bags also indicating the capping state.

Detailed test cycle

To better understand the test cycle, a single one will be illustrated below.

Time-in-torque	Capsule temperature	Settling time
200 ms	20^oC	0 h

Table 4.2: State of the example test cycle

First of all it is necessary to create a cam profile setting its parameters as explained before, or exporting it to a file from a CAD modelling software. In the latter case the cam profile has to be loaded in the machine memory. This is realized through the dedicated menu on the HMI as shown in figure 4.6

(a)

(b)

Figure 4.6: HMI menu to import the cam (a), invert it and assign an angular offset (b).

When loaded, it may be necessary to invert the direction of the cam through the special button and it is also useful to shift the entire profile of an angle so that the cycle stops at a specific point. Two curves may appear on the screen, but the profile to look at is the main one (blue line).

In this case the loaded cam has been inverted and the angular offset has been set to 100^o as shown in figure 4.6. This will make the cam end its cycle at the highest point of the profile, allowing an easy access to the capped sample.

The next step is to adjust the machine reference points. The linear motor can be manually actuated with two buttons on the panel and another one can be used to set the present cam position as the zero displacement point, that is the highest point of the profile (see figure 4.7).

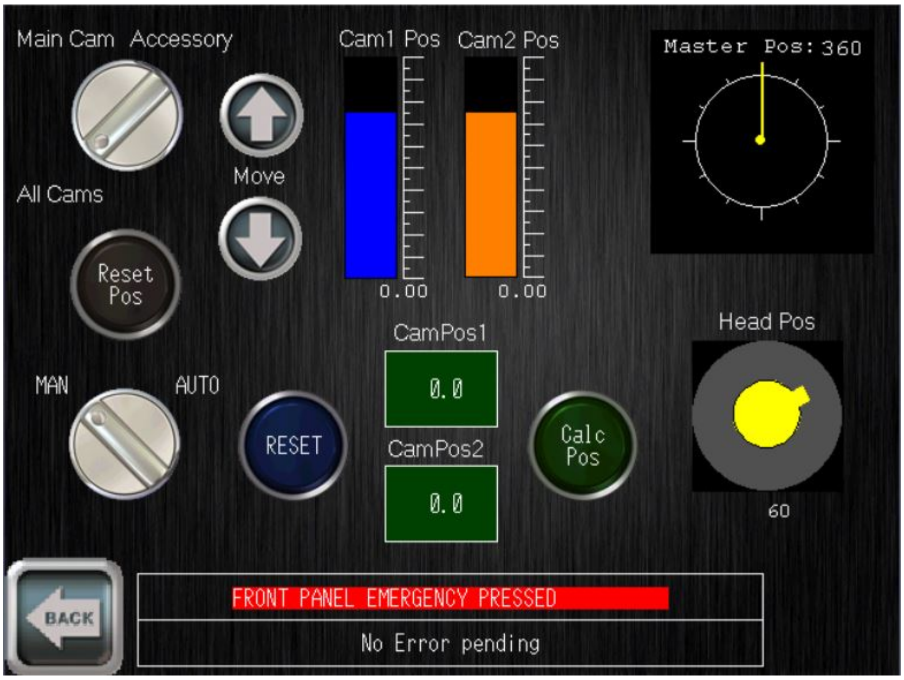


Figure 4.7: HMI page to set the initial cam position.

After that, it is necessary to regulate the height of the preform positioning apparatus. To do that, first a capped preform is inserted in the clamp, then the whole torque meter and clamp assembly is lowered by means of a lead screw and handwheel system. Next the execution of the cam profile is started at slow speed and paused at the bottom of the profile. Finally the positioning system is raised until the capsule of the preform is in contact with the capping cone and from there raised again of a precise amount. This last displacement, in this case it was 5 *mm*, compresses a spring mounted on the capping axis so that during the capping phase a specific top load on the bottle can be exerted. Figure 4.8 shows these steps in more detail.
With the last step, the cam profile execution can be resumed and the machine is almost ready for a test cycle. To complete the machine set-up, some capping parameters have to be changed in a menu as shown in figure 4.9. In this page it is possible to set the maximum closing torque, the cone spinning direction and time-in-torque, which will be set to 200 *ms*.
Before a cycle can be started, the torque meter has to be connected to a computer trough its signal conditioning unit and the dedicated software is launched as shown in figure 4.10.
Once the machine is ready, a preform is inserted in the special support and then fastened. Usually, at this point, a capsule is taken from the climatic chamber and its temperature is checked with a laser thermometer. To simplify this test cycle description, the cap

was taken at room temperature ($20\ ^oC$) and then placed under the capping cone.

Lastly the torque acquisition is started on the computer and just after that, the capping cycle is initiated. The testing machine closes the preform, the capping piston rises to the highest point of the cam profile and then stops. Figure 4.11 shows the testing machine before and after a preform is capped.

The data obtained from the torque meter mounted under the positioning system has not been used for this study, but it can be inspected to confirm the machine settings. As shown in picture 4.12 the torque measured during the closure rises up to a peak of around $16\ lbf\ in$ ($1.81\ N\ m$) and then it is maintained for $200\ ms$.

Once the preform has been capped, it can be released from the positioning system and brought to the opening-torque testing station.
This machine is equipped with a friction lock to prevent the preform from slipping when opened as shown in figure 4.13. The capped preform is placed on the machine, the tester head is regulated as needed and, through a menu on the HMI, the opening procedure is started. The machine records the torque exerted on the cap and displays the pitch value on the screen which is then manually written on a csv file. It is also possible to save the opening torque characteristics as the one shown in figure 3.2.

(a)

(b)

(c)

Figure 4.8: Adjusting the preform height (a), (b) and the spring compression (c).

Figure 4.9: Extract of a setup page on the HMI.

(a) (b)

Figure 4.10: Torque meter conditioner (a) and sampling software (b).

(a) (b)

Figure 4.11: The testing machine just before a cycle starts (a) and after it ends (b).

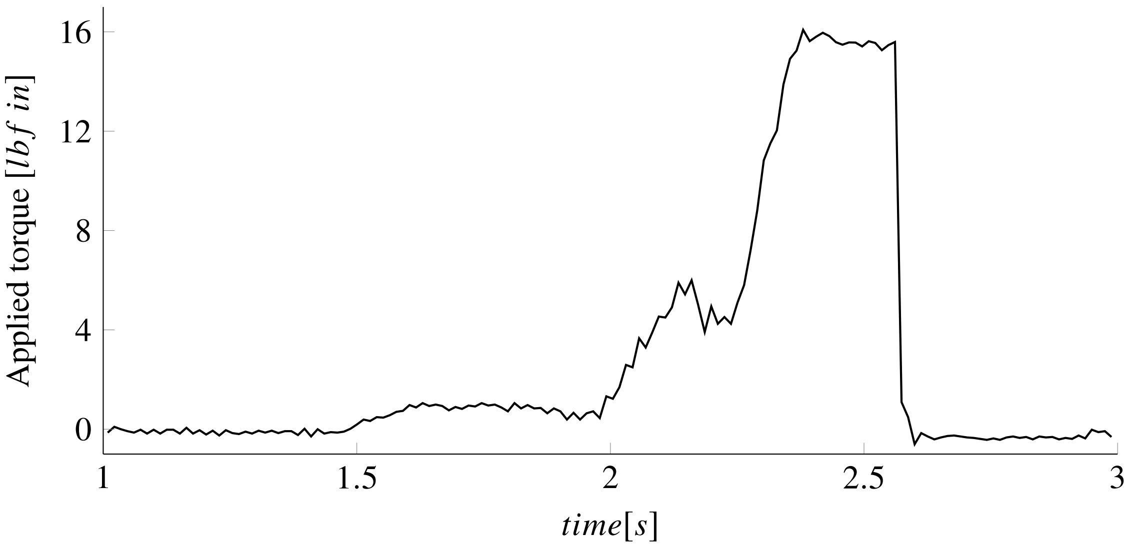
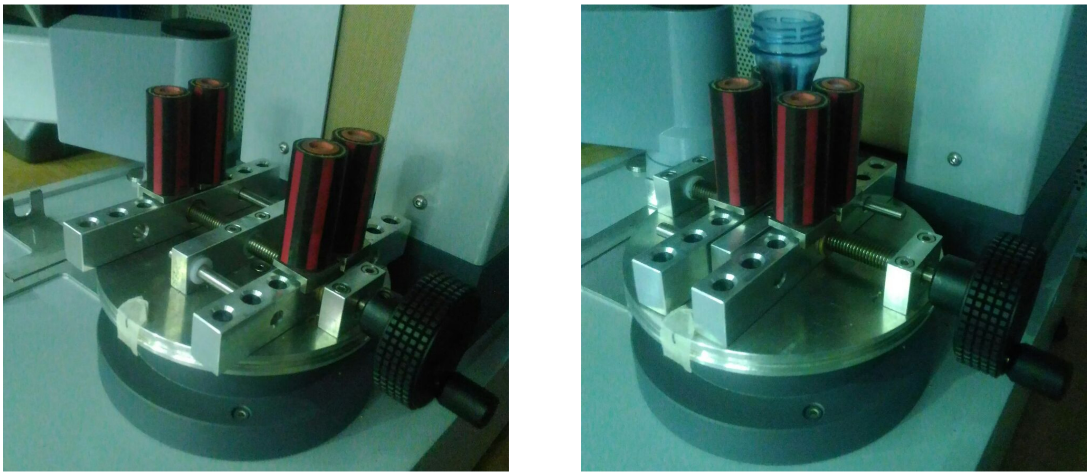


Figure 4.12: Example of closing torque characteristic.



(a)

(b)

Figure 4.13: the friction lock mechanism (a) on the opening torque testing machine (b).

4.3 Testing campaign #2

The result of the first testing campaign will be analysed in chapter 6. The approach followed to perform these tests is the same used for the first campaign, with the only exception of the parameters choice which is a consequence of the results obtained from testing campaign #1.

Design data

The type of cap and preform used for both campaigns is the same. The capping torque is now one of the varying parameters together with temperature, while time-in-torque is fixed to its optimum value found with the previous tests. Also, the settling time is set to the minimum value that allows to measure the opening torque as experienced by the end users.

With this setup, the influence of two parameters has been evaluated:

- Closing torque: with values in the range $13 \div 19\ lbf \cdot in$ $(1.47 \div 2.15\ N\ m)$
- Capsule temperature: with values in the range $15 \div 45\ ^oC$

For this test campaign, the closing torque has been varied 7 times, while temperature was taken with 4 different values. The results of the first set of tests suggested we should investigate further this specific temperature range, since the opening torque was more centred with respect to the specifications.
This time the number of samples has been increased to 11 for each of the 28 capping states, amounting to a total of 308 measurements.
A summary of the design data is shown in the table 4.3.

Varying the parameters

The closing torque is simply set on the HMI panel. As a consequence, the controller of the motor dedicated to the capping axis rotation sets a current limit. When the rotating cone starts to tighten the capsule on the bottle, the motor absorbs an increasing amount of current to keep a constant rotating speed. Once the set current limit is reached, the speed progressively decreases to zero while current, and therefore torque, remain constant for the specified time-in-torque interval.
The variation of temperature is obtained with a climatic chamber as explained in the previous section.
The analysis of the results is carried out in chapter 6.

Parameter	Value						
Cap	VR-28/1881						
Preform	PCO-1881						
Cam profile	Custom						
Capping head	Equatorque						
Capping torque $[N \cdot m]$	1.47	1.58	1.69	1.81	1.92	2.03	2.15
Top-load $[kg]$	25						
Closures for each test	11						
Time in torque $[ms]$	100						
Capping temperature $[^oC]$		15	25	35	45		
Settling time $[h]$	24						

Table 4.3: Summary of the design parameters for the second testing campaign

Chapter 5

Data manipulation

In the following pages, the data collected with the procedures explained in chapter 4 is elaborated and used to improve the capping process.

5.1 Statistical process control

Statistical process control defines the methods to use in order to improve a service or product [5]. In the case of this thesis work, the concept of process capability and performance will be mainly used to compare the data obtained in the different capping conditions as will be explained better later.

Causes of variations

Any process is subject to many sources of variability, therefore there can never be two identical products.
It is possible to make a distinction between the causes of these variations:

- *Common causes*: All the sources of variation that act consistently on the analysed process. They are often referred to as "natural problems" or "noise" and produce a repeatable distribution over time. If only common causes are present, the process is called "in statistical control" or just "in control" and its output is predictable.

- *Special causes*: Inte rmittent and unpredictable. These sources of variations have to be identified and acted upon, otherwise they may continue to impact the process output in unpredictable ways. When this type of causes is present, the process output will not be stable over time.

Currently, the capping process produces results within the specifications, nevertheless the process performance and capability can be improved finding the best capping conditions.

Process capability and performance

At the beginning of this chapter, two important terms have been introduced:

- *Process capability:* It derives from the process variation to determine its best performance that will be attained when the process is in statistical control. Only the variation is considered, not its location, i.e. the position of the measured average with respect to desired one.

- *Process performance:* It is a measure of how well a process output relates to the requirements, irrespective of its variation.

It is possible to quantify a process capability and performance, hence its compliance to the tolerances imposed by the specifications, with two indices:

C_p: This index measures how well a process satisfies the variability requirements. That is the maximum variation as indicated by the upper and lower limits of the specifications. C_p doesn't consider the process location.

C_{pk}: This index takes into account both process location and variation; a low C_{pk} signals that the process average is 'close' to the desired value, where 'close' is relative to the variation allowed by the specification range.

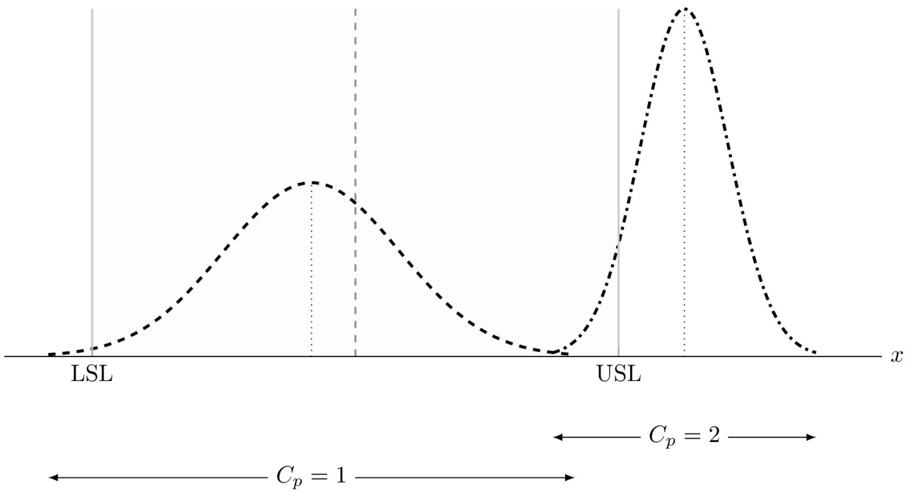
The formulas used to compute the indices are:

$$C_p = \frac{USL - LSL}{6\sigma}$$
$$C_{pk} = \min\left\{\frac{USL - \overline{X}}{3\sigma}, \frac{\overline{X} - LSL}{3\sigma}\right\}$$

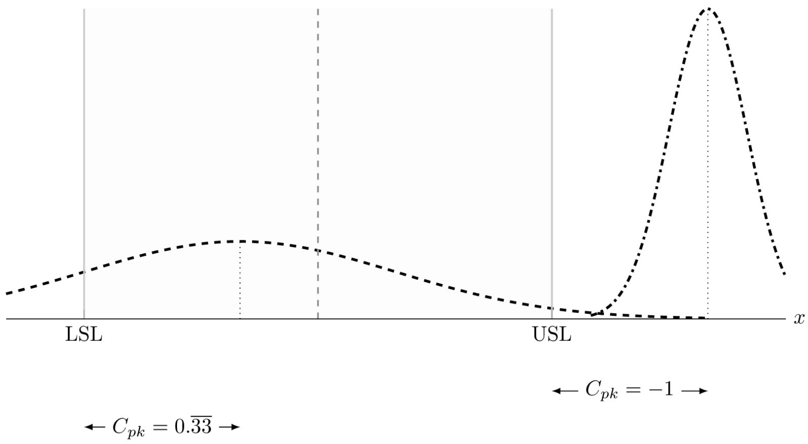
Where LSL and USL are respectively the lower and upper specification limit, $\overline{X}$ is the process average and σ is its standard deviation assuming a normal probability distribution.

Picture 5.1 illustrates the importance of reading both indices. For example in figure (a), the dash-dotted distribution has the best C_p, nevertheless it is outside the specification boundaries. Similarly in picture (b), the most centred distribution (highest C_{pk}) has a large standard deviation, making the process it describes not capable. Furthermore, it can be seen that C_{pk} can also be negative when the mean of the analysed distribution is outside the specification boundaries.
Thus it is important to take into account both indices when analysing a process.

The specification range for the opening torque is quite wide, therefore for the sake of improving the process, a more restrictive range has been used to compute the indices. This is the reason why the pictures that will be illustrated in chapter 6 show two boundaries.



(a)



(b)

Figure 5.1: Example of evaluating capable distributions when C_p is greater than 1 (*a*) and centred oneswhen C_{pk} $\in [0,\ 1]$ (*b*).

5.2 Organizing the samples and elaborating the data

For each of the two testing campaigns described in chapter 4, the data has been organized as follows:
A csv file has been created; The first two rows of the file contain its header in which are specified:

- A meaningful name for the data set
- The date when the data collection started
- a number n indicating the amount of varied parameters

The third row contains the names of the parameters that have been varied during the test campaign.
Finally, from the fourth row on, the measurements are stored.
The first n values refer to the capping state, so they represent a specific condition in which some samples have been measured. After those, there are the values obtained from the removal torque measuring device.
Each row of the file is relative to a capping state, so a combination of the n varying parameters, while the number of elements in the row is equal to $n + k$ where k is the number of closures per state.

Figure 5.2 shows part of the csv file used for the second testing campaign.

1	Test data 2	22-10-2018			
2	n	2			
3	Temperature [°C]	Closing torque [lbf in]			
4	15	13	8.31	8.34	9.52
5	15	14	8.45	9.12	10.17
6	15	15	9.46	9.66	11.2
7	15	16	10.97	10.63	11.53
8	15	17	11.6	10.78	11.04
9	15	18	10.57	11.84	12.07
10	15	19	11.94	12.14	14.42
11	25	13	14.06	9.52	10.55
12	25	14	10.85	12.23	11.61
13	25	15	12.01	13.18	12.56

Figure 5.2: Extract of a csv file containing the data of a testing campaign.

For the elaboration of the data, a python script has been developed using `pandas` and `matplotlib` as external modules.
The first one has been used to import the data from the csv, manipulate them using a tabular data structure called `DataFrames` and generate excel report files while the

second allowed the automatic generation of plots to better visualize the results.
The initial section of the script is dedicated to the settings, like indicating the path of the csv file, the length of its header section, the specification and project limits etc..
After these variables dedicated to the set-up, the steps performed by the script elaborating the data of the first data set are:

1) First the header of the csv is parsed obtaining the information about the name and date of the data set and, most importantly, the number of varied parameters during the tests (n).

2) The rest of the csv is imported into a table and sorted according to the capping parameters (or capping state).

3) A spreadsheet file with multiple pages is generated. The first one is a summary of the information on the data set while the others will be filled both by the original raw data and the elaborated set.

4) For each capping state, the k samples are used to compute the following:

    $\overline{X}$: The average of the samples.

    σ: The standard deviation of the samples.

    C_p: As discussed previously, to assess the process variability in this particular capping state.

    C_{pk}: The index to evaluate the location of the process in this capping state.

5) This newly computed data is saved in the previously mentioned spreadsheet.

6) The script selects three optimal capping states:

    - The one that minimizes σ.
    - The one that maximizes C_p.
    - The one that maximizes C_{pk}.

7) The normal distribution relative to each optimization is plotted on top of the chosen specification range as can be seen in figure 5.4. At the same time, three tables are created on another page of the spreadsheet containing the first few capping states that optimize σ, C_p and C_{pk}. The number of displayed elements can be set at the beginning of the script.

8) (optional) it is possible to repeat the previous step imposing a constraint on one or more parameters as can be seen, for example, in picture 5.5.

9) Finally a number of pictured is generated to better visualize the effect of each parameter in all the analysed capping states.

To better understand the last step of the data elaboration performed by the script, we can take the first data set as an example. In this case the varied parameters are three: Temperature, time-in-torque, and settling time.
As previously discussed in section 4.2, the values used for these parameters are:
$[10^oC,\ 20^oC,\ 30^oC,\ 40^oC,\ 50^oC]$ for temperature,
$[0ms,\ 50ms,\ 100ms,\ 200ms,\ 300ms,\ 400ms,\ 500ms]$ for time-in-torque.
$[0h,\ 24h,\ 48h]$ for setting time.

Twenty-one pictures have been generated by the script to investigate the effect of temperature; one for each combination of the time-in-torque and settling time. In each of the pictures are represented five curves, that are the probability distributions relative to the different values of temperature. To reduce the amount of produced files, the pictures have been grouped in a single pdf file.
Similarly, to understand the effect of time in torque, fifteen pictures have been produced (one for each combination of temperature and settling time) in which there are seven curves (one for each value of time-in-torque). An example is shown in picture 5.3.

In general, if we have n parameters, indicating with p_i the number of values of the i-th parameter, the script will produce N_i plots with p_i curves in it:

$$N_i = \prod_{j=1,\ j\neq i}^{n} p_j$$

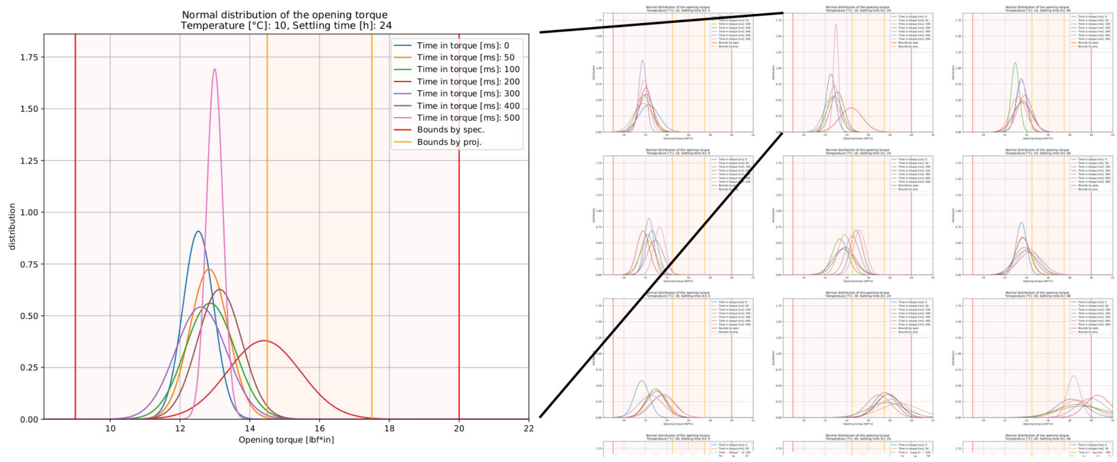


Figure 5.3: Example for visualizing the effect of time-in-torque on the opening torque.

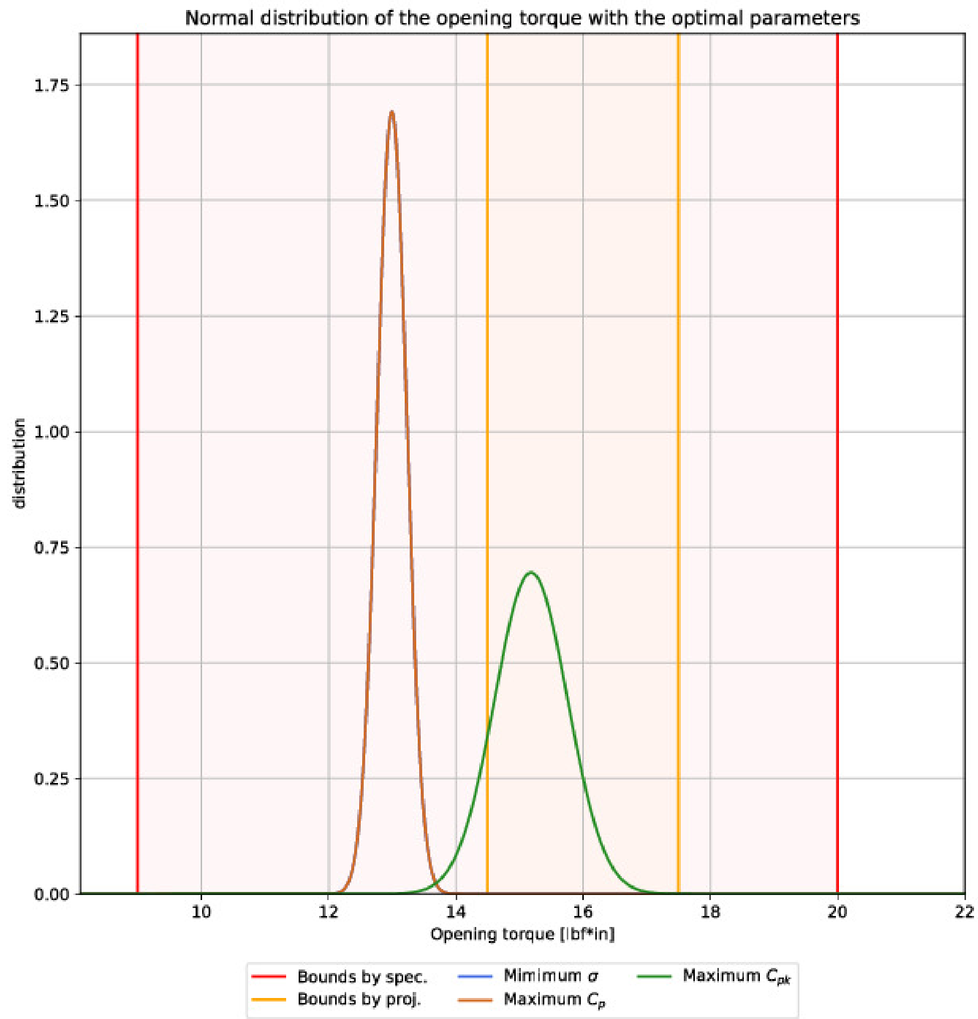
The script used to elaborate the data of the second testing campaign is different from the previous one; It uses the same principles to select the optimal curves, but it works with this logic:

1) The csv with the raw data is imported. It will contain just temperature and torque as parameters.

2) At first, only the data relative to the nominal torque is selected. The value assumed as nominal is the one indicated by the cap manufacturer.

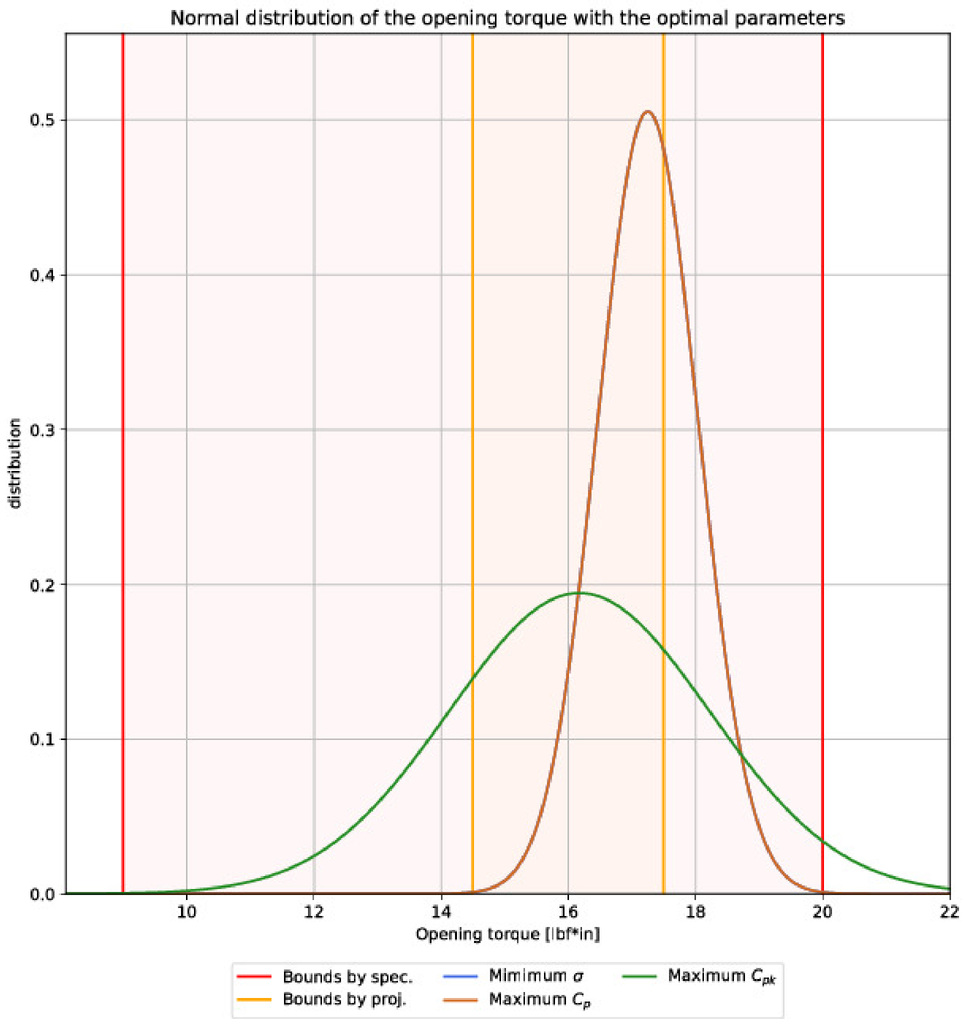
3) With the isolated values, the probability distributions relative to all the tested temperature values are compared on a plot and the best value is selected automatically based on the index C_{pk}.

4) Again from the initial csv, the data obtained with the newly found best-temperature value is selected and step 3 is repeated obtaining an optimal closing torque.



	Minimum σ	maximum C_p	maximum C_{pk}
Temperature [°C]	10.00	10.00	20.00
Time in torque [ms]	500.00	500.00	500.00
Settling time [h]	24.00	24.00	24.00
Average	12.99	12.99	15.18
Std	0.24	0.24	0.57
Cp	2.12	2.12	0.87
Cpk	-2.13	-2.13	0.40

Figure 5.4: The three distributions (two overlap) relative to the optimal capping states and a table listing them.



	Minimum σ	maximum C_p	maximum C_{pk}
Temperature [°C]	50.00	50.00	50.00
Time in torque [ms]	300.00	300.00	100.00
Settling time [h]	24.00	24.00	48.00
Average	17.25	17.25	16.17
Std	0.79	0.79	2.05
Cp	0.63	0.63	0.24
Cpk	0.10	0.10	0.22

Figure 5.5: The three distributions (two overlap) relative to the optimal capping states and a table listing them, with the temperature constrained to 50^oC.

Chapter 6

Conclusion

The information obtained from the first data set has been used to obtain an approximate idea of the optimal capping state. With this knowledge it has been possible to continue with the second testing campaign and obtain the final results.

6.1 Results of testing campaign # 1

First of all, the effect of temperature has been analysed.
As shown in fig 6.1, the results obtained after an immediate opening are concentrated in a small band below the lower project specification limit unlike the openings at 24 h and 48 h which produce similar results with a trend towards the higher removal torque values. Therefore it can be assumed that after one day the preform material has had enough time to settle and the opening torque is stabilized. For this reason all the removal torque samples of the second testing campaign have been taken after 24 h.
After that, the influence of temperature has been evaluated.
In line with the previous paragraph, only the data relative to 24 h and 48 h settling time are shown in figure 6.2. As indicated in the picture, each of the plot column is dedicated to a different settling time, while time-in-torque and temperature are represented respectively on the horizontal and vertical axis of each plot. The area of every plot is a sort of capping state space indicating the capping conditions.
The circles of the two top bubble chart give an idea of the change in average removal torque with the capping state, whereas bottom plots indicate the standard deviation σ of the samples.

Inspecting the images it can be seen that the value of removal torque tends to increase above 20 ^oC, while σ rises significantly between 40 ^oC and 50 ^oC. To make sure that this effect depends mainly on the temperature and it is not due to the low number of samples, the sample number has been increased to 11 for the second dataset. Also

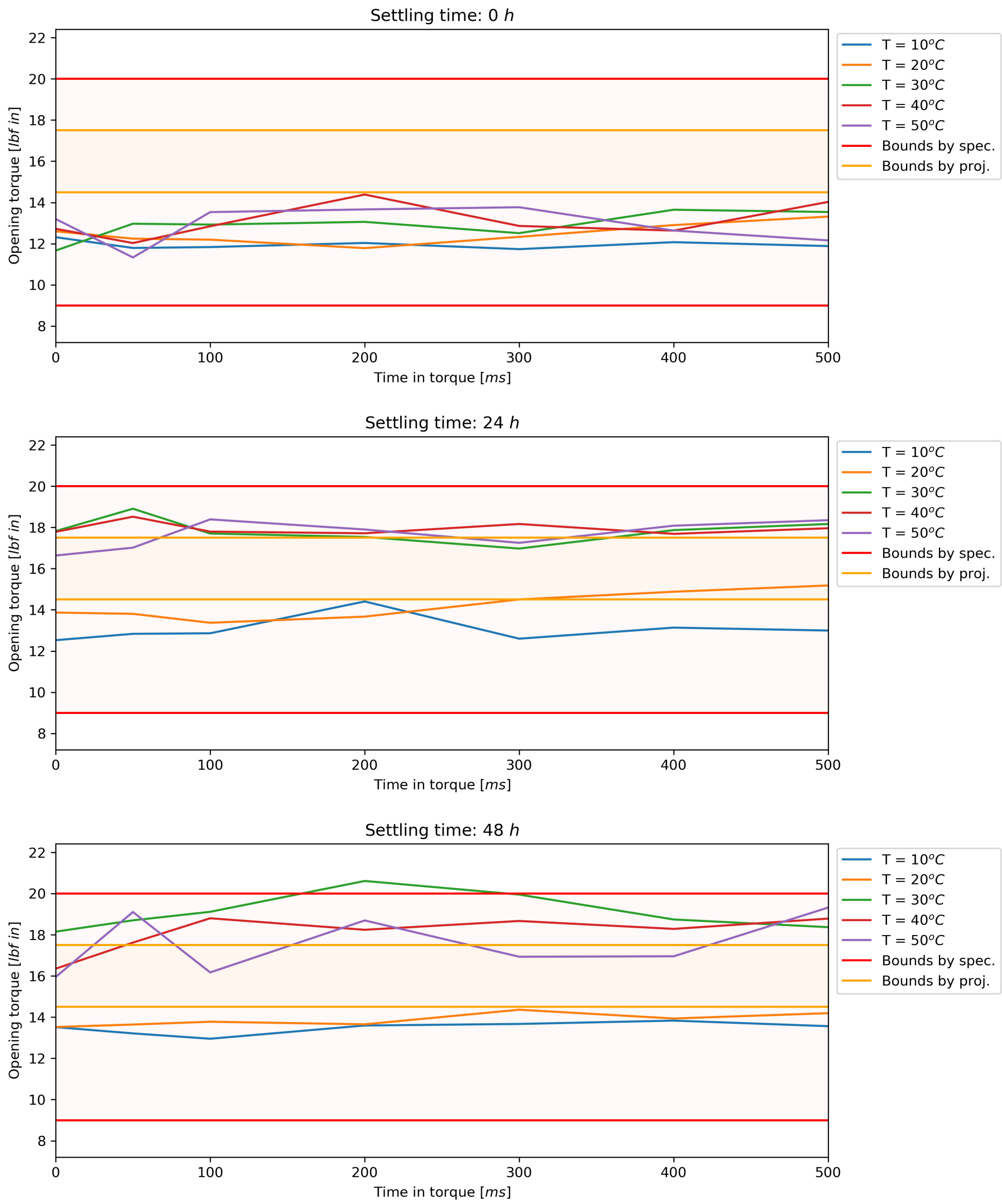


Figure 6.1: Removal torque after different settling time intervals.

the values of temperature have been reduced and concentrated in the region between $15 \div 45^oC$.
After that, the influence of the time-in-torque has been analysed since, as explained in

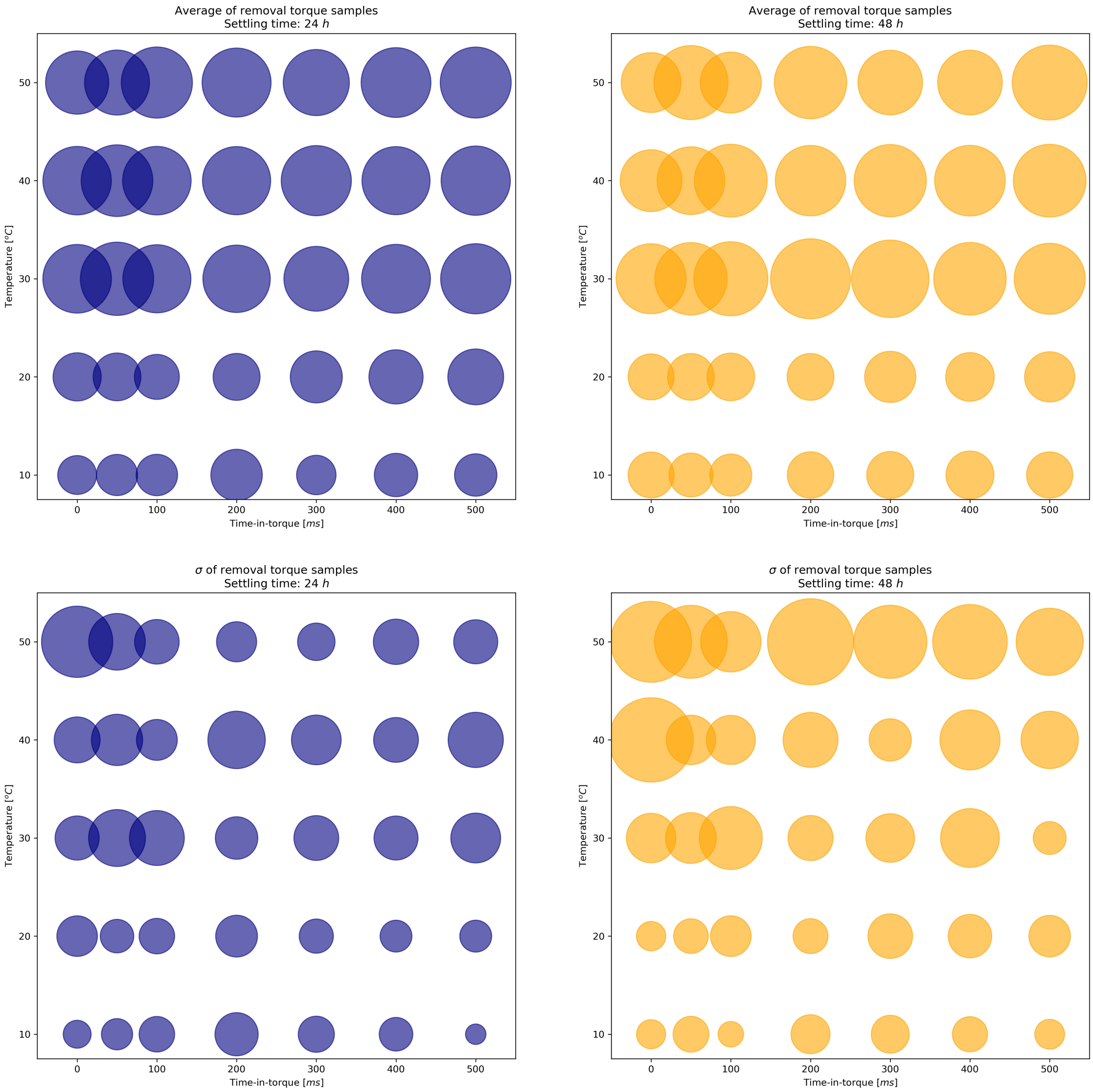


Figure 6.2: Average removal torque in various conditions with a settling time of 0h.

section 4.1, it directly affects the design of the capping machine.

Figure 6.2 shows that the variation of time-in-torque doesn't have a great impact on the removal torque after 100 *ms*. This confirms that the capping machines used buy the company are already optimized under this aspect. As a consequence, the second testing campaign uses a fixed value of time-in-torque equal to 100 *ms*.

Now that the results of the first data elaboration have been explained, the conditions used for the second campaign should appear more sensible.

6.2 Results of testing campaign # 2

As briefly explained in chapter 5, the data obtained at the nominal closing torque are sorted in order of decreasing C_{pk} and the best one is selected. As shown in figure 6.3 each distribution refers to one value of temperature and the best curve is the one at 45 ^oC. It follows that the next plot generated by the script collects the data at $T = 45^oC$ and shows one curve for each value of closing torque. In figure 6.4 the best value appears to be 17 $lbf \cdot in$ (1.92 $N\ m$) which is in fact confirmed by the last picture 6.5.

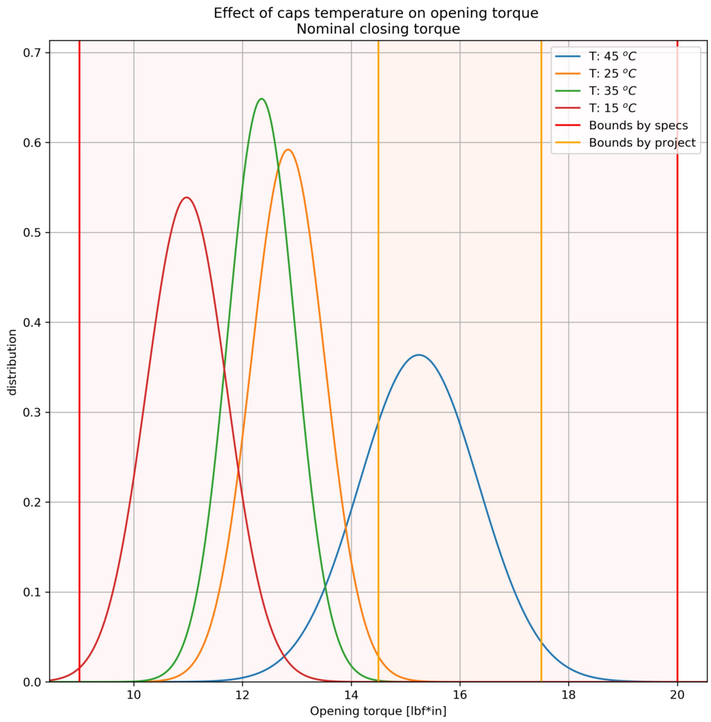


Figure 6.3: Effect of the different temperature values on the opening torque.

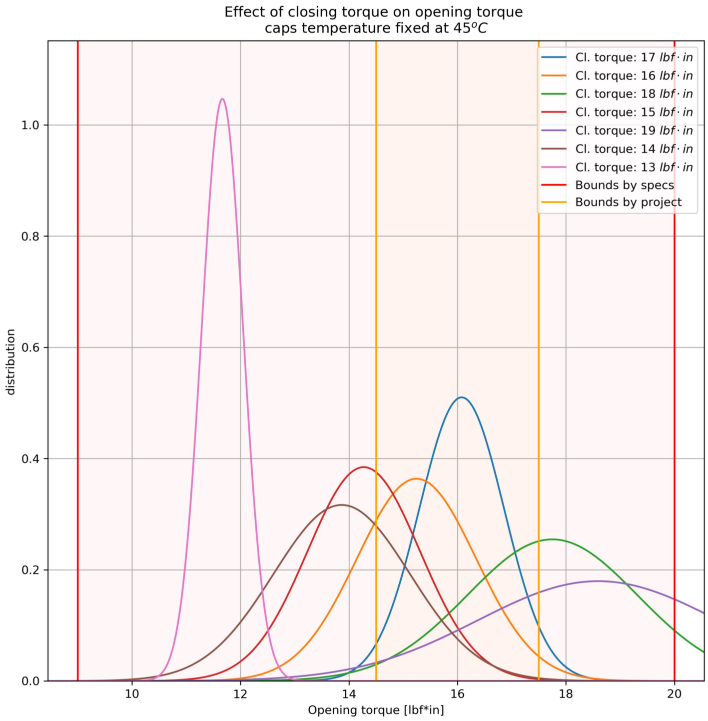


Figure 6.4: Effect of the different closing torque values on the opening torque.

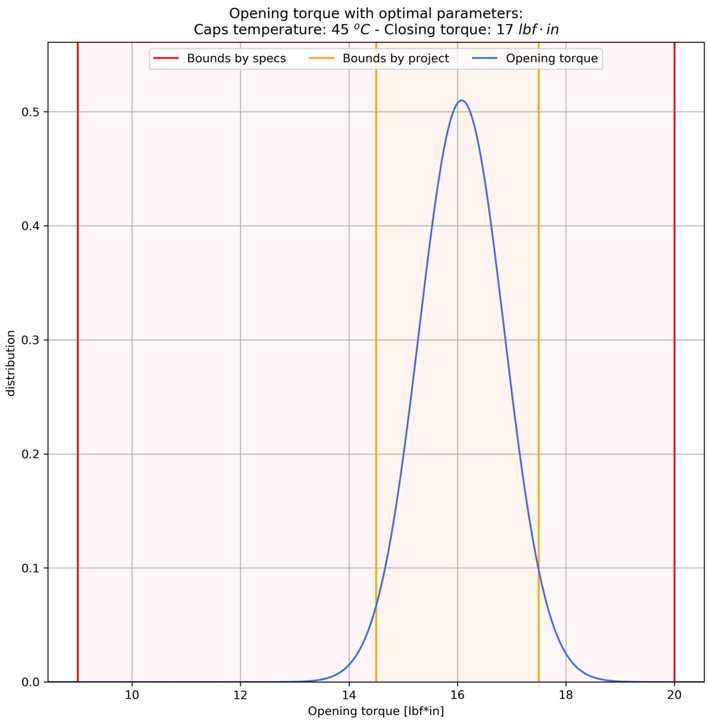


Figure 6.5: Result with the optimal parameters.

6.3 Summary and future developments

This thesis work has demonstrated a procedure to attain the best capping conditions for a specific cap-preform combination to obtain a removal torque within a specification range. Of the many identified parameters affecting the capping process, only the few most influential ones have been analysed. Nonetheless more than a thousand measurements have been made and an optimal parameter combination has bees found. A bit of automation has been introduced in the data analysis phase with two scripts; Changing the settings on those scripts allows to easily and quickly repeat the analysis with different specifications. Certainly, for this thesis work, the number of tests has been maintained relatively low choosing carefully the values of the capping parameters. In the near future, the objective is to obtain a more complete characterization of the cap-preform removal torque as a function of the many input parameters; This will involve a much more abundant quantity of measurements and it is evident that such a procedure would be tedious and prone to human error. That is why the testing system will have to be automated. The main idea on how to evolve the project is to introduce an anthropomorphic manipulator which moves the capping axis. Other than that, a few more changes will have to be made to the current system to be able to automate it in a significant way. With a bigger set of data, it will be possible to identify the best capping conditions for many more specification ranges with greater confidence on the quality of the results.

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