BIPM Capacity Building & Knowledge Transfer Programme

2023 BIPM - TÜBİTAK UME Project Placement

REPORT

Field of metrology:	Study of the Physical Characteristics of a Torque Standard Machine to a Future Development at Colombia's NMI
Description:	In this project, the fundamentals of the main standards, principal components (pieces and structure), physical-mathematical models, and the contributions of uncertainty that constitute the Tübitak UME torque standard machines were studied to understand their behaviour. Additionally, a detailed review of the main calibration standards for torque measuring instruments was realized. The previous work will allow the knowledge transference and support the basis for future research and development of a torque standard machine at Colombia's NIM.
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Date	September 3rd, 2023 to December 1st, 2023.

Motivation & Introduction

The mechanical magnitude of Torque is an integral part of the science and the industry worldwide, and for this reason, it is essential to have a robust national metrological traceability system. Colombia is in a growth process in several fields, which is why the development of measurement standard machines is essential, especially for the Torque laboratory of the National Institute of Metrology of Colombia (NIM), since the existing ones are mid-hierarchical. The construction of standard machines in the NIM would allow metrological traceability to be provided in the region, inducing development in the industry, and additionally, it would position the country as a reference, since currently only a few institutes can provide Torque metrological traceability in America.

Despite there being a lot of information related to the development of Torque standard machines, it is important to have advice from metrologists specialized in the development of torque standard machines, in this case by the Tübitak-UME Torque laboratory work team[1], given that several additional considerations that must be taken into account and that are usually ignored in the literature. For this reason, the sixth cycle of "BIPM–TÜBİTAK UME project placements" is the indicated opportunity to lay the background and main supports to be able to structure a proposal for a future research project in the development of primary and secondary Torque standard machines, the which could also support development other projects in the parallel like as Force and Hardness laboratories.

It is essential to know first-hand the traceability chain, the standards generally used between the different echelons, and the main characteristics of the machines; Therefore, first of all, the main standards were studied, encompassing that are at the base of the metrological traceability chain, which range from the

[1] The main scientific reference articles used in this visit are (Doğan, Akkoyunlu, & Kuzu, 2002), (Doğan, Tunaci, A. Bin Jarbua, & M. Alqarni, 2022) and (Doğan, Tunaci, A. Bin Jarbua, & M. Alqarni, 50 N·m Torque Standard Machine at SASO/NMCC, 2022) these support the machines developed at Tübitak-UME.

calibration of hand torque tools to the calibration of Torque transducers. Within the review, was participated in some practices as an observer and others under supervision.
Subsequently, a detailed review of the main components and general operation of the Dead Weight Torque Standard Machines (DWMs) and the Reference Torque Standard Machines (RSM) was developed. The review included the analysis of some of the most important components and the physical properties more relevant used for the construction of the machines, focusing on the reduction of uncertainty budgets.
Finally, the components of uncertainty, the impact of their contributions, and their nature were analyzed individually, which is part of the development process of standard machines and defines their potential to be used as Torque standard machines.

Research

The research project was based on the "waterfall" methodology to achieve the proposed objectives; it was structured into three main objectives, linked to the development of Torque standard machines:

1. Understanding the Torque Traceability Chain

To study the most relevant characteristics of Torque standard machines, it is necessary to delve deeper into the connection between the different levels of the metrological traceability pyramid, where these connections are mediated through calibration standards. During the visit, a review, reproduction, and interpretation of the most recognized standards for the traceability of static and quasi-static Torque were carried out, and the most representative aspects are explained below:

- ***Assembly tools for screws and nuts - Hand torque tools - ISO 6789-1 y ISO 6789-2***

These standards are part of the basis of the metrological traceability chain, where the reference standard is a torque measurement system, which is generally a torque wrench calibration device[2]. The instruments to be calibrated are classified into torque indication tools (Type I) and torque adjustment tools (Type II), where the main difference is that in the tools of the first type, there is some type of indicator that shows the result of the measurement, and in the other simply its internal structure is designed in such a way that when applying a specific torque an impulse is generated that indicates that it has been reached[3], which allows comparison with the standard.

- ***Guideline DKD-R 10-8 Static calibration of calibration devices for torque wrenches***

It is necessary to calibrate the Torque wrench calibration devices and for this purpose, the Torque transfer wrench[4] is used. It is very important to add that among the most notable aspects of this type of calibration is that the possible mounting configurations define the calibration routine; these are related to the degree of angular freedom of the measurement sensor in the device and of the connection profile fixed associated with the Instrument under calibration (IUC). This is one of the most important aspects and the ones that have been most emphasized in the revision of this standard since it usually confuses.

- ***Guideline DKD-R 3-7 Static calibration of indicating Torque wrenches***

This standard supports the metrological traceability of Torque transfer wrenches and other types of Torque wrenches that have higher accuracy, from this point the RSM begins to provide metrological traceability. One of the most important variables in this part of the process is related to the application of force at the indicated point of the Torque transfer wrench and involves the imposition of conditions on the

[2] In most cases this device is a torque bench.
[3] Usually, the signal makes a click sound, but it is not something canonical.
[4] In the literature it is also known as torque reference wrench, but it is linked to previous versions of the standard.

design of the machine, for example, ensuring the greatest possible perpendicularity of the position vector and the force vector.

- ***Calibration of Static torque measuring devices - DIN 51309***

The aim is to provide traceability to Torque measurement instruments such as Torque transducers, and some manual Torque measurement instruments, among other torque measurement instruments that do not depend on an arm for the application of Torque and are instead uniaxial, through RSM and DWSM. The difference concerning the previous standard is that the uncertainty due to having a Torque transfer arm and the effect of Hysteresis are omitted, despite the error of this last effect being calculated.

- ***Guidelines on the calibration of Static torque measuring devices – EURAMET Cg14***

This standard seeks the same objective as DIN 51309 and both are considered complementary to each other. This standard was also reviewed in this paper because the core of the project is based on the development of Torque standard machines and precisely this standard also contemplates the use of the physical principles under which the RSM and DWSM work.
Other additional standards can support the previous ones that were not reviewed in detail, among which (ASME, 2004) and (The British Standards Institution, 2017) stand out.

2. Study of the most important components and characteristics

Figure 1. shows a representation of the two types of 50 kN.m standard machines present at Tübitak-UME and their main parts. Some of the previous pieces are explained below.

2.1 DWM characteristics

DWMs are the primary standards of Torque magnitude, that is, they allow direct traceability to the SI. These are based on the definition of the magnitude of Torque under certain simplifications associated with the type of system, which allows the realization of the magnitude.
The basic principle is an arm from which masses are suspended that generate a moment due to the local acceleration of gravity. If the physical quantities (such as length, mass, gravitational acceleration, among others) that can influence the generation of the dynamic moment are controlled and characterized, this constitutes the basis for a good primary reference standard.

- **Main structure**

Supports the entire machine and is sufficiently robust for insulating the rest of the machine's components do not feel the effects of parasitic forces significantly. Sometimes the structure is floor-mounted to support the torque induced by the masses (Carbonell, Verdecia, & Robledo, 2006), and generally, its structure is made with welded and bolted steel.

- **Fulcrum**

The fulcrum is one of the most important pieces in a standard torque machine because this piece supports the arm. When a knowing mass is suspended at the end of the arm It generates a defined Torque that is compensated by the Torque induced by the transducer connected to the motor. Therefore, the error sources in this subsystem are strongly related to the lever length and the moment produced between the transducer and the frame, through the fulcrum. This Torque is commonly known as torque shunt and depends exclusively on the fulcrum (Gassmann, Allgeier, & Kolwinski, 2000). Usually, there are two principal kinds of fulcrums:

- Aerostatic bearing

It piece allows absorption of multiple transverse forces if the pressure used is enough to ensure the major quantity loss of friction. In Tübitak UME's 1 kN.m machine, the pressure used is around 500 kPa (Doğan, Akkoyunlu, & Kuzu, 2002), which is also supported in other machines (Carbonell, Verdecia, & Robledo, 2006), (Doğan, Tunaci, A. Bin Jarbua, & M. Alqarni, 50 N·m Torque Standard Machine at SASO/NMCC, 2022) and (Röske, 1997).

- Flexure bearing

It consists of a set of pieces of elastic hinges, which are independently and simultaneously moveable when applying force on the lever arm (Arksonnarong, Saenkhum, Chantaraksa, & Sanponpute, 2019).

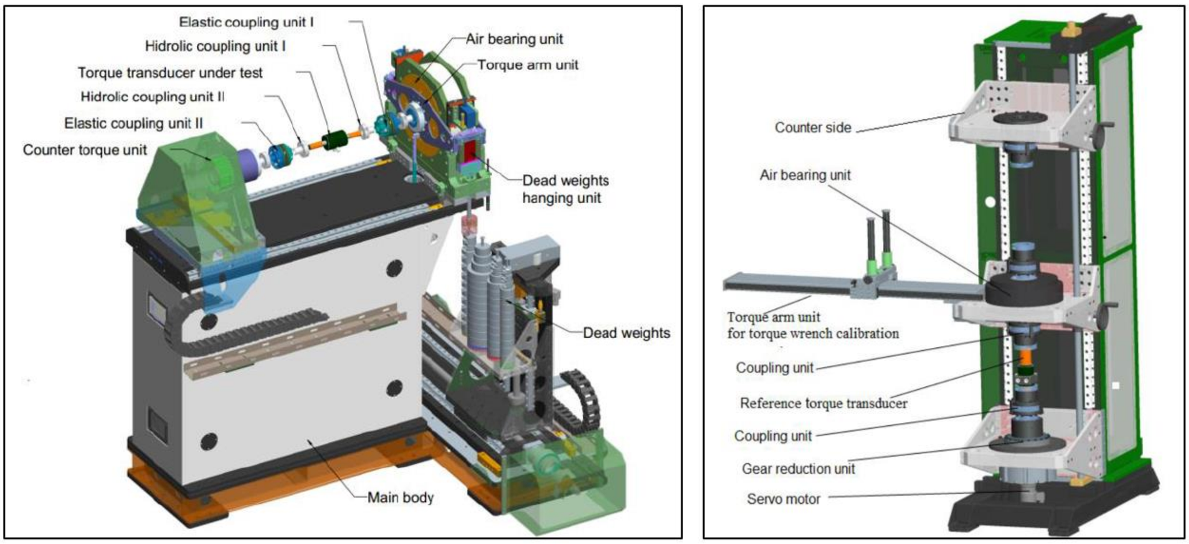

Figure 1. *The left shows the DWSM and the right the RSM. Images were taken from* (Doğan, Tunaci, A. Bin Jarbua, & M. Alqarni, 50 N·m Torque Standard Machine at SASO/NMCC, 2022) *and* (Doğan, Tunaci, A. Bin Jarbua, & M. Alqarni, 2022)*, respectively.*

- **Lever arm**

The arm level is just the mechanism to transmit the loads wanting. Is important has present that the lever arm is composed of two main Invar plates connected.
The main reason for using these types of materials is that they have thermal expansion coefficients of the order of $10^{-7}\ °C^{-1}$ (Carbonell, Verdecia, & Robledo, 2006) and (Röske, 1997). The Invar steels present must be machined, avoiding heating them to preserve the physical properties.
Another important aspect is to characterize well the length of this arm because the torque is directly influenced by the application radius of the load. In the Tübitak UME Torque laboratory, the length characterization was realized with a 3D coordinate machine (CMM) traceable to national standards of Length.
The arm lever tilt is controlled by two position sensors located just above the arm extremes. The arm lever tilt is controlled by two position sensors located just above the arm extremes, ensuring the minimal variation possible, for example, the 50 kN.m Tübitak UME Torque standard machine the distance guaranteed is ±10 µm (Doğan, Tunaci, A. Bin Jarbua, & M. Alqarni, 50 N·m Torque Standard Machine at SASO/NMCC, 2022).

In some cases, a fin-shaped compartment is mounted at the bottom of the torque arm and immersed in a chamber of viscous fluid to reduce the vibration level of the Torque arm (Yon-Kyu, Min-Seok, & Dae-Im, 2007).

- **Suspension Mechanism of Weights**

There are two main kinds the pieces to control the bending moments and to adjust the lever arm position, these are the elastic hinges and metal bands. When the metal bands are screwed this effect produces non-deseeded mechanical tensions and pressures on the surface of the band metal generating inconsistency in the measurements, then is necessary to screw the bolds with a specific Torque predefined and maintain control over this torque posteriorly.
One of the most direct solutions is to use elastic hinges in place of metal bands, however, this kind of system broadly is more expensive and presents more installation difficulties, due to the elastic hinges working with strain-gauged that verify possible parasitic bending moment.
Another alternative is to use the same metallic bands but roll in horizontal pins to generate friction enough to suspend the maximum set of masses[5].

- **Weight sets and tray**

The 1 kN.m DWSM has two sets of masses for the two extremes of the arm lever, respectively. Furthermore, on each side, there are 6 mass subsets composed of 13 masses where the masses are stacked on top of each other reaching a maximum load of 2200 N. It is only possible to load a subset of masses at a time, where a rotating platform is available to change subsets.
On the other hand, the 50 N.m machine has a different system for applying the load, which only requires one set of masses for the two ends of the arm, and the masses are stacked on top of each other reaching a maximum load of 220 N. The loading system consists of a mobile platform mounted on a rail that goes in the same direction in which the level arm is arranged, which means that only a set of masses is required, composed of three subassemblies that move in one direction or another. direction to generate Torque clockwise or counterclockwise. The mass uncertainties of the torque Tübitak UME DWSMs are respectively better than 3 ppm (Doğan, Akkoyunlu, & Kuzu, 2002) and 7 ppm (Doğan, Tunaci, A. Bin Jarbua, & M. Alqarni, 50 N·m Torque Standard Machine at SASO/NMCC, 2022).
Specifically speaking of the design of the masses exist two principal options: the first is the typical chain model of masses connected with the adjacent masses such as the masses are supported in a horizontal table moving vertically and unhanging them one by one. The second is a binary model where the masses are connected but is possible to interchange the masses allowing all the possible combinations of loads integers between the maximum and the minimum permitted loads. The last system is very useful for calibrating all intermedial loads, to a difference of the first model in which the applied loads are restringed, however, it's important to consider that the binary model is more expensive due to the complexity.
An important detail is that the masses must be protected with an outer cover from humidity and air currents that could cause them to oscillate.

- **Parts for counter-torque application**

The counter-Torque is developed by a servomotor together with a harmonic drive gearbox. This type of gearbox has a high load capacity and great precision; additionally, it usually has less weight and dimensions than other types of harmonic drive gearboxes. In the Tübitak UME 50 N.m DWSM the gearbox reduction ratio is 1:10,000 including a 13-bit absolute encoder for the servomotor (Doğan, Tunaci, A. Bin Jarbua, & M. Alqarni, 50 N·m Torque Standard Machine at SASO/NMCC, 2022). The encoder provides a certain position with respect to

[5] The rolling bands are not a good solution in the regimen of low loads.

another static reference position, and its resolution is given by the bits or number of pulses per revolution (PPR), which are defined as 360° divided by the degrees to be measured.
On the other hand, the motor is supported by a moving part that allows the motor to be moved further or closer to the air bearing, depending on the characteristics of the IUC.

- **Parts for Transducer Coupling**

There are different components to coupling the transducer between the motor and the air bearing, and these are commercial pieces that are standardized. The most important are presented next:

a. Hydraulic expansion bushes

This piece allows adjusting the adaptation between different sizes of the shaft end. A hexagon head bolt on the lateral side increase or decrease the pressure inside of the coupling allowing the connection of two different parts.

b. Flexible steel couplings

This kind of coupling always is necessary to try aligning the axis of the torque produced by the motor and the generated by the lever arm and, avoid parasitic mechanical moments. The coupling has a low bending and axial stiffness propitiating the aligning of the axes. In general, the aim is to reduce the distance between axes, so that it is almost zero, since if the previous condition is not met, an unwanted moment of inertial md^2 may exist between the reference transducer and the IUC, where m represents the mass of an object under rotation and d is the distance between the body under rotation and the rotation axis[6]. Figure 2. shows the schematic situation of the previous situation in the RTM case.

c. Cylindrical steel flanges, squared in/output connectors, and metallic extensors

On some torque measuring equipment, the output of these transducers has an adapter that must be screwed on with bolts, and is necessary uses cylindrical steel flanges. There are other common connector configurations with square inputs or outputs that allow transducers to be attached. Additionally, metal extenders can be used, although their use should be avoided if they are too extensive and the machine allows the distances to be adjusted.

- **Operational System**

The operational system in the Tübitak UME Torque standard machines is construed by the motors previously mentioned, connected to the user human interface (HMI) through a PLC that directs the communication signals, as is usual.
Regarding the capacity of the operation software, it is worth adding that it is important that this software allows manual and automatic operation. Among the most important options should be the ability to choose the calibration direction, the reading instrument, and the capacity of the transducer. Additionally, it must allow the creation and editing of different calibration routines, including load application times. The software must also provide information about errors in the operation of the machine, attempting to accurately describe the location of the failure and a possible cause.

[6] This principle is supported by the Huygens–Steiner Theorem. For more details see for instance (Kleppner & Kolenkow, 2014).

2.2 RSM characteristics

In this type of Torque standard machine, the Torque is performed by a servomotor and the counter-Torque is supported by the structure that holds the IUC. There are different variants, where for example, the layout of this machine is completely horizontal. This machine has a great advantage since it allows the calibration of Torque tools, Torque reference wrenches, and Torque transducers, however, its uncertainty is greater than the primary standard machine's uncertainty because depends of the Torque reference transducer is the standard of the RSM.

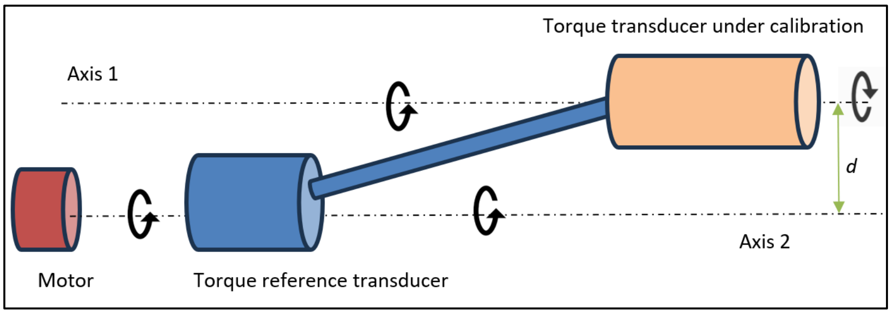

Figure 2. *The schematic setup of the RSM and the differences between axes. The motor is anchored and its transmission movement system tries to generate rotation on the reference Torque transducer, and then it transmits the dynamical momentum to the reference transducer which is fixed, inducing a counter-Torque to keep the quasi-staticity of the system.*

- **Principal structures**

The structure follows almost the same guidelines as the DWSM structure; however, this frame can also be manufactured with aluminium. In all cases, the frame must be designed in such a way as to ensure that it will support the loads; this is previously studied through simulations.

- **Support counter-side**

The upper counter side allows you to hold the IUC that will be calibrated. It is important because it must withstand the Torque generated by the lower motor, which is why it must be verified through simulations that there is no considerable angular deflection. This upper counter side can move vertically, which can be done through a manual mechanism or through an electric motor.

- **Support air bearing unit**

The intermediate piece supports the air bearing and the Torque arm unit. It also has a degree of freedom in movement, vertically helped by a manual mechanism or through an electric motor.

- **Support motor and gear reduction unit**

This piece allows for keeping supported and aligning the motor's system with its respective drive gearbox. Additionally, this piece is embedded in the frame structure and must support parasitic bending. It is important to keep in mind that the main structure and the different supports must be designed in such a way that they support high loads, around 10 times the maximum applied Torque.

- **Torque reference transducer**

The reference transducer is one of the most important components of the RTM because this allows the machine's behavior to be characterized through the characteristic equations (one for each load direction) obtained after calibrating it on a primary standard Torque machine. Subsequently, the Torque to be applied by the motor is determined by the signal in mV/V transformed with an equation, resulting in the indicated load.
A single RTM can have several associated torque transducers, for example, in the Tübitak UME Torque laboratory, the following reference transducers stand out:
- (5, 10 ,20, 50) N.m for 50 N.m RTSM.
- (20, 50 ,100, 200, 500, 1000) N.m for 1000 N.m RSM.

- **Torque arm unit:**

This component is necessary to calibrate Torque transfer wrenches and Torque wrenches, likewise to calibrate hand Torque tools. This arm is composed of a horizontal support that protrudes from the machine and a composite piece where the arm of the IUC is supported. Specifically, the composite part supporting the arm has a structure as shown in Figure 3. It is composed of two vertical rollers and one horizontal roller, which can be adjusted horizontally and vertically. The idea is that these rollers allow the IUC arm to slide and support at the same time, trying to keep the contact between these pieces as minimal as possible to reduce possible unwanted forces.

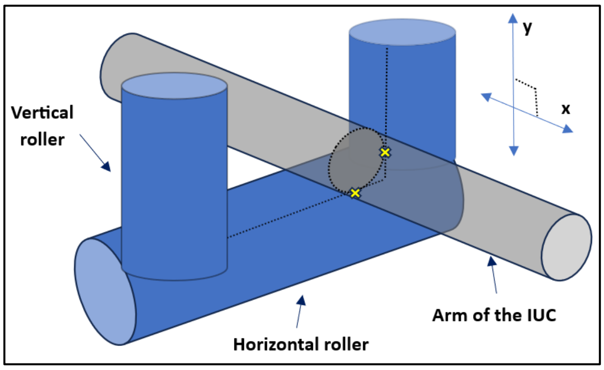

Figure 3. *Schematic representation of the piece of the arm support, where the yellow cross indicates the two theoretical intersection points between the rollers and the IUC arm.*

Other of the most important components of this type of machine that have already been detailed previously are:

- **The aerostatic bearing**
- **The motor and gearbox generate Torque**[7]
- **Hydraulic expansion bushes**
- **Flexible steel couplings**
- **Cylindrical steel flanges, square inlet/outlet connectors and metal extenders**
- **Operation system**[8]

[7] In the case of the Tübitak UME's RSM of 1 kN.m, the reduction of the transmission box is 1:5000 and a 13-bit absolute encoder is used (Doğan, Tunaci, A. Bin Jarbua, & M. Alqarni, 2022).
[8] This varies in programming concerning the DWSM system since the measurement systems are different. In fact, in the case of the DWSM, the operating system is simpler, since it only has to move and apply the loads, so it does not constantly require communication and does not strictly require a PID. The opposite occurs with the RSM since the communication must be almost simultaneously throughout the process.

3. Analysis of uncertainty budgets

The following analysis delves into the uncertainty components that are the most representative in the development of Torque standard machines.
In general, in science, a base model is usually proposed that represents a certain phenomenon as best as possible, and as more information is known, it is complemented, where the above is done through mathematical relationships or through the ability to extract experimental information. The way to choose a base model will depend on the advantages or disadvantages it presents when developing calculations or inferring approximations. To estimate the Torque, two mathematical models are usually used: the sum model and the product model, which are represented in equations (1) and (2), respectively.

$$\tau = \tau_0 + \sum_{i=1}^{n} \delta\tau_i \tag{1}$$

$$\tau = \tau_0 \prod_{i=1}^{n} (1 - \delta\tau_i) \tag{2}$$

With τ_0 being the most representative contribution of Torque, $\delta\tau_i$ the disturbances related by additional secondary Torque components.

3.1 Identification and analysis of the uncertainty components of the DWSM

In the case of a primary Torque model, it is possible to start with the following relationship that considers the main Torque contributions[9], without significant disturbances and which are compensated by the electric motor to maintain static balance,

$$\tau_0 = \tau_g + \tau_{bouy} \tag{3}$$

Where τ_g is the gravitational Torque induced by the hanging mass and τ_{bouy} the counter-Torque induced by the buoyancy of the masses in the air. From which follows the following relationship:

$$\tau_0 = \left(1 - \frac{\rho_{air}}{\rho}\right) mgl \sin\theta \tag{4}$$

Where ρ_{air} and ρ represent the density of the air and the mass m. Also, g and l represent respectively the local acceleration of gravity and the length of the arm from the point of support to the end that supports the mass. It is important to recognize that θ indicates the angle between the force vector and the position vector. The previous relationship can be further simplified in the sense of working with a linear expression concerning the angle, applying the fact that we will work with $\theta \approx {}^{\pi}/_{2}$, which reduces $\sin\theta \approx 1 + \mathcal{O}_2\left(\left(\theta - {}^{\pi}/_{2}\right)^2\right)$ and (4) can be rewritten as (5) and include the contribution associated with the angle as perturbations to the base model.

$$\tau_0 = \left(1 - \frac{\rho_{air}}{\rho}\right) mgl \tag{5}$$

It is important to note that this basic relationship could be as complex as desired, including other variables from the beginning, for example, the length depends on other variables such as temperature, and yet the variation is small compared to the main torque, so it is usually included as a correction. The general expression proposal is made based on expression (1).

[9] "Main contributions" are understood as those that constitute a high percentage of the measured torque.

$$\tau = \left(1 - \frac{\rho_{air}}{\rho}\right) mgl + \sum_{i=1}^{n} \delta\tau_i \tag{6}$$

The sensitivity coefficients of (6) can be calculated for each of the variables by applying the differential operator ∂_i to τ, those budgets are contained in Table 1. The main components that constitute the uncertainty budget are:

- **Mass**

The Mass uncertainty has an associated normal distribution and is obtained specifically from the calibration of specially designed mass subsets. The average mass relative uncertainty of some of the main DWSMs, with capacities between 20 N.m to 1 kN.m is approximately 1.7×10^{-5}. It is important to keep in mind that when small masses are worked, such that they generate a Torque of the order of 2 N.m, these are usually made of aluminium to reduce the volume occupied by the masses. In the case of Tübitak UME, they manufacture the dough themselves and provide traceability with their Mass laboratory.

Table 1. *Sensitivity components for relation (6), where* (JCGM, BIPM, 2008) *was used as a guide.*

Variable	**Sensitivity coefficient**	**Relative uncertainty components** [10] $\boldsymbol{w_j(\tau)}$
m	$\frac{\tau_0}{m}$	$w_m(\tau) \equiv \frac{u(m)}{m}$
g	$\frac{\tau_0}{g}$	$w_g(\tau) \equiv \frac{u(g)}{g}$
l	$\frac{\tau_0}{l}$	$w_l(\tau) \equiv \frac{u(l)}{l}$
ρ_{air}	$-\frac{\tau_0}{\rho - \rho_{air}}$	$w_{\rho_{air}}(\tau) \equiv -\frac{1}{\rho - \rho_{air}} u(\rho_{air}) = -\frac{\rho_{air}}{\rho - \rho_{air}} w(\rho_{air})$
ρ	$\left(\frac{\rho_{air}}{\rho}\right)\frac{\tau_0}{\rho - \rho_{air}}$	$w_\rho(\tau) \equiv \left(\frac{\rho_{air}}{\rho}\right)\frac{1}{\rho - \rho_{air}} u(\rho) = \frac{\rho_{air}}{\rho - \rho_{air}} w(\rho)$
$\delta\tau_i$	1	$w_{\delta\tau_i}(\tau) \equiv \frac{u(\delta\tau_i)}{\delta\tau_i} = w(\delta\tau_i)$

- **Air density**

This magnitude is related to the buoyancy of the masses that generate the main Torque. To find the respective density of the air, the following approximate expression can be used, taken from (OIML R111, 2004):

$$\rho_{air} = \frac{0.34848P - 0.009He^{0.061T}}{273.15 + T} \tag{7}$$

[10] Here the sensitivity coefficient c_i and the associated absolute uncertainty are included in the component $u(x_j)$.

Where P [hPa] is the Barometric pressure, H [%] is the Relative humidity, and T [°C] is the Temperature. Furthermore, the associated uncertainty components are:

$$w_P(\rho_{air}) = \frac{0.34848P}{273.15 + T} w(P) \tag{8}$$

$$w_H(\rho_{air}) = -\frac{0.009He^{0.061T}}{273.15 + T} w(H) \tag{9}$$

$$w_T(\rho_{air}) = -\frac{\rho_{air} + 5.49 \times 10^{-4} He^{0.061T}}{273.15 + T} Tw(T) \tag{10}$$

The three uncertainty terms for calculating the uncertainty of the air can be extracted from measurements in the laboratory where it is desired to estimate the density of the air, for instance, through measurements developed with a thermohygrobarometer. The way to determine the estimated air density $\rho_{air}(P, H, T)$ recommended by (JCGM, BIPM, 2008) is by calculating the $\overline{\rho_{air}}(P, H, T)$ instead of $\rho_{air}(\bar{P}, \bar{H}, \bar{T})$, because the function $\rho_{air}(P, H, T)$ is non-linear. To estimate the uncertainty of the air density $w(\rho_{air})(P, H, T, w_P, w_H, w_T)$ the previous recommendation can be followed and the uncertainties of the variables P, H, and T can be acquired from a calibration certificate. The measurements should consider different moments where the environmental conditions are varied.

- **Mass density**

The Mass density usually has a rectangular distribution associated with itself. Furthermore, to provide metrological traceability, the masses are first sent to be calibrated with the density laboratory and subsequently with the mass laboratory. Because the uncertainty is usually about an order of magnitude lower than the uncertainty of air, some authors omit to explicitly include this term, which is the order $\sim 10^{-7}$ and usually include it all in the Density of air.

- **Local acceleration of the gravity**

It usually has a normal distribution; however, some authors prefer to work with it as a rectangular distribution (Park, Kim, & Kang, 2007) and (Jile, Kun, Bin, Shi, & Zhimin, 2021). Importantly, the estimated uncertainty at the usual workplace must consider variations in measurements over a significant period and should be monitored depending on the stability of measurements and environmental conditions. Due to the above, stable infrastructure is required (preferably underground) to obtain the best performance from the torque standard machine, and the base that supports the machine should be a specially constructed pile to be as uniform as possible.

On the other hand, variations in Local acceleration of gravity must be minimal, avoiding the existence of significant sources of local variation in gravitational acceleration, for example, verifying that there are no underground water sources.

The best instruments to be able to trace this magnitude are Absolute gravimeters which support absolute uncertainties in the order of $\sim 10^{-8}\ {}^{m}/_{s^2}$ a $\sim 10^{-7}\ {}^{m}/_{s^2}$, and additionally, it is possible to control the Acceleration of gravity and its uncertainty through the use of Relative gravimeters through a point transfer procedure. The important thing is to take into account that the relative uncertainty contributed by the Relative gravimeter added to that of the reference point is of the order $\sim 10^{-6}$, although generally the contribution of uncertainty due to the Acceleration of gravity in Torque standard machines is usually among the lowest.

- **Length**

The Length presents several variations in its measurement and these uncertainties are mainly due to the following sources: inaccurate measurement, deviation from the nominal value[11], Temperature variation, horizontality of the arm, and flexion of the arm.
The measurement of the arm length generates inaccurate measurement uncertainty, which is measured before being installed and was carried out with a 3D coordinate measurement machine traceable with the SI, to then estimate its uncertainty. The latter can be obtained directly from the calibration certificate. Additionally, these measurements provide the variation in the thickness of the metal bands.
The variation of Length with Temperature $l(T)$ can usually be expressed with the linear relationship of thermal contraction and expansion:

$$\Delta l(T) = L\alpha\Delta T \tag{11}$$

Where L and α are constants that represent the length without variation due to temperature changes and the thermal expansion coefficient of the material, respectively. ΔT can be treated as a variable representing the temperature variation. It is clear from the previous relationship that, if working in the laboratory under controlled temperature conditions, for example, $\Delta T \approx 2\ °C$, it becomes essential to have an arm made of a material with a low α. Among the cases reported in the literature, where the uncertainty w_T is higher, there is the case of $w_T = 9.2 \times 10^{-6}$ with a temperature difference of $\Delta T \pm 1\ °C$, this implies that the arm has a $\alpha = 1.6 \times 10^{-5}\ °C^{-1}$, this corresponds to the thermal sensitivity coefficient of austenitic stainless steel. Many times, finding materials with a low thermal coefficient is expensive, so a possible recommendation is to design the arm with more than one material and thus have an effective thermal sensitivity coefficient that remains low.
On the other hand, the DWSM arm usually has two sensors at the ends of it, these sensors ensure the horizontality of the arm, for example, with a displacement sensor (laser) whose control margin of $\pm 20\ \mu m$ and an arm of total length $500\ mm$, an angular control margin of $\pm 0.0046°$ is obtained, which generates a relative uncertainty of 1.85×10^{-9} (Park, Kim, & Kang, 2007). To calculate the uncertainty, the following relationship is used, based on Figure 4.

$$w_\varphi(l) \equiv \frac{u(\varphi)}{L} = \frac{1 - \cos(\varphi)}{\sqrt{3}} \tag{12}$$

Note that a rectangular distribution is used, where $L \equiv |\vec{r}|$ represents the length of the arm from the point of support to its extreme and φ the angle of inclination.
Finally, the bending of the arm is generated by a torque generated by the hanging masses and by the arm's weight, Figure 5. shows details of the effect. To estimate this uncertainty component, first, the bending contribution is calculated based on a physical and a mathematical argument: the first is the basic equation of the theory of bending deformation (moment-curvature equation) (Timoshenko, 1940) and the second is the definition of the radius of curvature R $(\mathrm{Stewart}, 2012)$, both are related in equations (13) and (14), respectively.

$$\frac{1}{R} = \frac{M(x)}{EI} \tag{13}$$

$$\frac{1}{R} = \frac{\frac{d^2y}{dx^2}}{\left(1 + \left(\frac{dy}{dx}\right)^2\right)^{3/2}} \approx \frac{d^2y}{dx^2} \qquad if\ \frac{dy}{dx} \ll 1 \tag{14}$$

[11] This source of uncertainty is obtained through the traceability laboratory for length and is of the form $w_{Nom}(l) \equiv \frac{u(Nom)}{L}$.

Where $M(x)$ is the bending moment, E is the elastic modulus of the material, I is the moment of inertia or second momentum. Furthermore, y represents the deflection, and x is the distance from the support point, as shown in Figure 5.

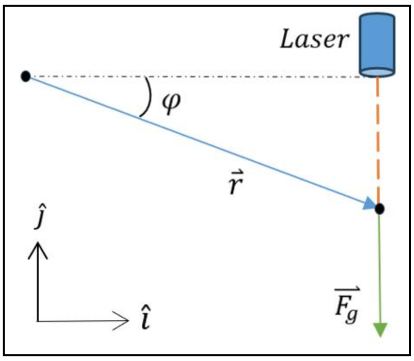

***Figure 4**. Arm inclination diagram. The orange line represents the beam interacting with the arm to measure tilt distance.*

Relating equations (13) and (14), integrating twice and simplifying, we obtain:

$$y = \int\left(\int \frac{M(x)}{EI} dx\right) dx = \frac{1}{EI}\left(-\frac{Fx^3}{6} + Ax + B\right)$$

Where the bending moment for this case behaves linearly as $-Fx$. Simplifying with boundary conditions $\left.\frac{dy}{dx}\right|_{x=L} = 0$ and $y|_{x=L} = 0$, and rewriting, we obtain equation (15).

$$y = \frac{FL^3}{3EI}\left(-\frac{1}{2}\left(\frac{x}{L}\right)^3 + \frac{3}{2}\frac{x}{L} - 1\right) \tag{15}$$

The previous relationship agrees with the relationship for the variation of flexion provided by (Röske, 1997). The correct thing would be to verify the variation of the torque when the arm is curved, however, when the arc length is calculated in this type of system the difference can be neglected[12]**.** The above implies that the arm can be treated as a straight structure and the uncertainty can be estimated more easily, using the expression (16).

$$w_\beta(l) = \frac{FL^2 \tan(\beta)}{\sqrt{27}EI} \tag{16}$$

Where β can be easily calculated as $\tan(\beta) = \left.\frac{dy}{dx}\right|_{x=L}$. It is important to note that the vertical component of the deflection varied in $\frac{FL^3}{3EI}$ and is compared with respect to the length L.

- **Air bearing friction**

The most used air bearings for metrology applications are generally H-type. The way to know the uncertainty can be directly from the indications given by the air-bearing manufacturer or through experimental observations. The problem with obtaining the estimate directly from the information provided by the manufacturer is that it usually includes the maximum possible value, which could penalize the uncertainty of other load levels.

[12] Here they also show that the arm varies its length in the deflection process, but this change is negligible for practical purposes, of the order of 10^{-8} m for the predefined parameters.

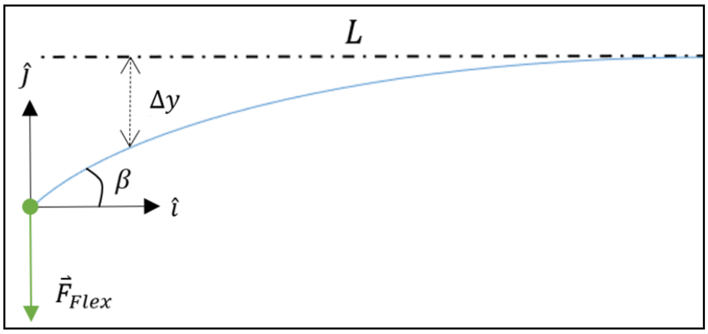

***Figure 5**. Diagram of the bending experienced by the arm. Note that It is worked with an Effective force, mainly associated with the Gravitational force, at the end of the arm.*

The Friction force generates a Torque in the opposite direction to the Torque that is desired to be generated by the action of the hanging masses. The main way to analyze the uncertainty due to Friction with the air bearing is by applying small known loads to the system in equilibrium and characterizing the variation of the reading in the digital amplifier. Another alternative is to put the system in equilibrium, then small masses are placed and the critical angle β_{crit} is verified in the static regime. Figure 6. shows a diagram of the situation described. Subsequently, after using Newton's second law and calculating the Friction force, the mathematical expression (17) is obtained that better explains how to calculate the uncertainty with this methodology. This component of uncertainty is generally one of the most significant among the different budgets to the total uncertainty and in this case, a rectangular distribution is assumed.

$$w_{\delta_{fr}}(\tau) = \frac{u(\delta_{fr})}{F_{inf}} = \frac{\Delta F_{fr}}{\sqrt{3}F_{inf}}$$

$$w_{\delta_{fr}}(\tau) = \frac{F_{crit}\cos(\beta_{crit})}{\sqrt{3}F_{inf}} \tag{17}$$

It should be taken into account that F_{crit} represents the Gravitational acceleration force obtained by the maximum mass added to obtain β_{crit} and F_{inf} the Force generated by each one of the masses used, where β_{crit} implicitly includes the associated Friction coefficient.

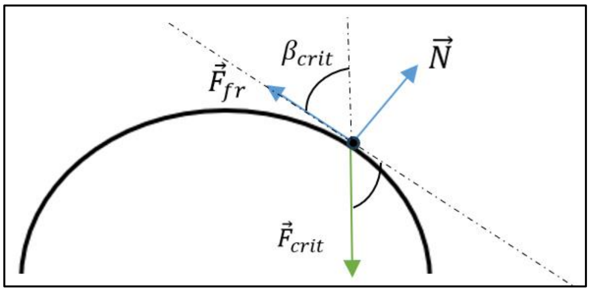

***Figure 6**. Diagram of the forces associated with friction uncertainty.*

- **Other contributions**

They highlight the uncertainty due to the oscillation of the masses, external electromagnetic sources, vibrations, and parasitic torque moments (such as having the counter torque motor shaft system misaligned with the air bearing, among others[13]). Generally, these last contributions tend to be less representative, concerning the main assumptions of uncertainty that were previously explained, if they are kept controlled, for example, by keeping electromagnetic sources far away and making measurements of them whenever there is the possibility of having

[13] See for example (Van Duy, Toan Thang, & Van Hung, 2017)

this type of external disturbance. Finally, a review of the most representative components in different DWSM[14] has been done, see Figure 7. to verify the most relevant components and analyze some trends.

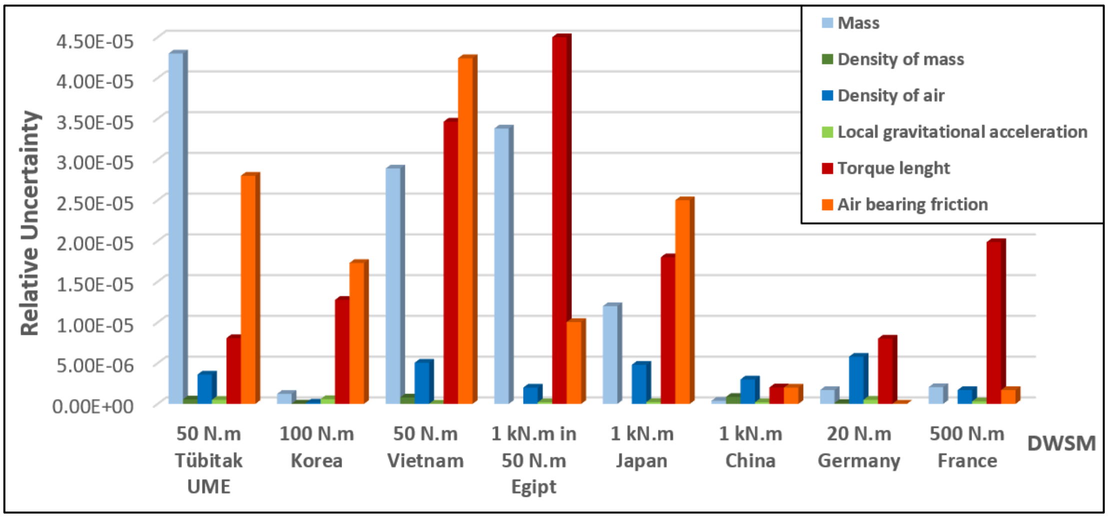

Figure 7. *Distribution of the main sources of relative uncertainty in DWSM. In the graph, the relative uncertainty for the component associated with the Torque length for the Egyptian machine is* 1.46×10^{-4} and the graph was restricted to better visualize the other components.

3.2 Identification and analysis of the uncertainty components of the RTM

For the analysis of the uncertainty of the RTM, the mathematical model of the product (2) will be used, where the base torque contribution is the torque in the reference transducer (TRT). The main sources of uncertainty are listed below in Table 2.

- **The source of uncertainty due to the standard machine**

In this case, the contribution was described in the description of the uncertainty of the DWSM, imposing a limit due to the sum of each one of the other contributions having an uncertainty higher or equal to that of the DWSM uncertainty. According to the experience of the Tübitak UME torque laboratory staff, the most usual range of expanded relative uncertainty in DWM in general in other institutes covers $2 \times 10^{-5} < W_{\mathrm{DWSM}} < 5 \times 10^{-4}$, ergo, the most usual range of expanded relative uncertainty in DWM is between $1 \times 10^{-4} < W_{\mathrm{RTM}} < 5 \times 10^{-3}$.

- **Uncertainty due to the temperature change in the TRT**

Table 2 shows a dependence of the thermal sensitivity coefficient α of the reference transducer and the temperature variation ΔT assuming a rectangular distribution. Therefore, a maximum variation of $\pm 1\,K$ throughout the calibration is usually explicitly stated in the main calibration standards (DIN - German Institute for Standardization, 2005) and (EURAMET, 2011). The sensitivity coefficient is acquired from the datasheet of the torque transducer or its previous certificate, if this coefficient is not known, experiments can be carried out to find it or estimate it theoretically (ISO, 2011).

[14] The information was processed from (Doğan, Tunaci, A. Bin Jarbua, & M. Alqarni, 2022), (Jile, Kun, Bin, Shi, & Zhimin, 2021), (Park, Kim, & Kang, 2007), (Van Duy, Toan Thang, & Van Hung, 2017), (Duflon & Averlant, 2020), (Khaled & Aggag, 2022), (Nishino, Ogushi, & Ueda, 2013), and (Schlegel, Röske, Mauersberger, & Hohmann, 2018).

- **Uncertainty due to long-term stability in the TRT**

This component is associated with the natural variation of the properties of the reference transducer. It is related to the variation $\Delta\tau$ of the measurements obtained in previous calibrations concerning the nominal torque value and to the long-term stability coefficient ν, which can be estimated through a mathematical model[15], for instance, inferring a linear relationship or being extracted from the transducer datasheet, if it includes it.

Table 2. *Uncertainty components for the RTM based on* (Doğan, Tunaci, A. Bin Jarbua, & M. Alqarni, 2022).

Source of uncertainty	**Variable**	**Relative uncertainty components $w_j(\tau)$**
DWSM	δ_{Std}	$w_{\delta_{Std}}(\tau) \equiv \frac{W(\delta_{Std})}{k}$
Temperature change in TRT	δ_{Temp}	$w_{\delta_{Temp}}(\tau) \equiv \frac{\alpha\Delta T}{\sqrt{3}}$
Long-term stability on TRT	δ_{Long}	$w_{\delta_{Long}}(\tau) \equiv \frac{\nu\Delta\tau}{\sqrt{3}}$
Creep in the TRT	δ_{Creep}	$w_{\delta_{Creep}}(\tau) \equiv \frac{\mathrm{c}}{\sqrt{3}}$

- **Uncertainty due to creep**

The creep error c is defined in the standard (DIN - German Institute for Standardization, 2005) as: $c \equiv \frac{(L_1 - L_0)}{M_E}$, where L_1 is the reading just before the first series of measurements and L_0 the reading just after finishing the third preload, where there must be a time interval of 180 s. Furthermore, M_E is the upper limit of applied torque. On the other hand, there are additional components to those presented in Table 2, such as[16]:

- Alignment of the torque transmission shaft between transducers.
- Fricción of the air bearing.
- Bending moments due to fail of horizontality.
- Influence of couplings
- Bending moment when calibrating torque reference wrenches

The sources of uncertainty mentioned above usually have relative uncertainties of orders of magnitude less than or equal to 10^{-6}, which can be ensured if quality parts are used and a process of design, construction, and assembly of the machines is carried out. careful. For example, in the machine assembly process, a verification of the horizontality of the supports of the torque generating motor, the air-bearing, and the upper counter-torque structure must be carried out.

Conclusions and Future Work

[15] For more details about mathematical modeling, refer to (JCGM, 2020).
[16] More sources of uncertainty can be found (Doğan, Tunaci, A. Bin Jarbua, & M. Alqarni, 2022).

Knowledge of the complete torque traceability chain, through the analysis of the standards and the interaction with the standard machines and other torque measurement instruments, was essential to understand the challenges to be assumed in future developments of standard machines from a broader perspective of the bases of the dissemination of the magnitude was acquired, and additionally, the learning will allow the improvement of processes that are developed within the torque laboratory and even processes that could be carried out inappropriately in the Colombian industry.

The understanding of the main components, the structure, the dynamics, and the sources of uncertainty inherent to the different types of torque standard machines will allow us to lay the foundations for a future research proposal for the development of standard machines in Colombia.

It was found that within the DWSM construction process, the most representative variables of the measurements are the uncertainty of the arm length and the uncertainty contributed by the air-bearing system, therefore special emphasis should be placed on these components, previously to the design and build of the machines process be started.

On the other hand, the RTM is more viable concerning the number of sources of uncertainty, the difficulty in construction, and the economic cost. In addition, the RTM can offer the possibility of developing calibrations at high loads for both torque transducers and torque transfer wrenches; however, it does not provide direct traceability, which could increase long-term traceability costs due to the need to calibrate the TRTs. There must be detailed information on the needs of the industry, metrological traceability in the region, and cost analysis, to provide the best solution for the country and the region. Therefore, it is advisable to have both types of machines in the Colombian Torque laboratory, because internal traceability could be provided to the equipment, not only at the national level but also at the regional level.

Additionally, the learning acquired about the functioning of the BIPM, the structure of the CIPM MRA, and the role they play in metrology worldwide, allows the appropriation of robust knowledge to support the technical and quality area in light of the development of machines as potential standards for metrological traceability.

The knowledge transfer process began slowly from the moment the visit to Tübitak UME began, subsequently, it will intensify upon arrival in Colombia with the work team of the different laboratories that can support a future development of the magnitude of torque in the NIM. In addition, the knowledge acquired will be put at the service of other magnitudes for the improvement of other laboratories. It is hoped to be able to work with the Tübitak UME's Torque laboratory in future research projects.

Acknowledgments

First, I would like to thank the support of the BIMP program and Tübitak UME for providing economic, location, and logistical support in the development of the project, and additionally, to the NIM for the additional financial support and cooperation to be able to participate in the stay, with the accompaniment of the Subdirectorate of Physics Metrology department.

On the other hand, the guide to reach each one of the proposed objectives was fundamental, as the support in the calibration exercises, and in general, the discussions held with the work team of the Tübitak UME's Torque laboratory, constituted by the experts: Mr. Çetin Doğan (Head of the Torque laboratory) and Mr. Semih Tunacı doing that the complete experience was very enriching and full of knowledging, all time I perceived great fraternity feeling me like as home, both in the laboratory and with the rest of the Tübitak UME staff. I would like to give additional thanks to Mrs. Müge Atam, from the International Relations Department, for her support from the beginning and for making all possible arrangements necessary to have a great stay.

Finally, the multiple spaces provided by Mr. Juan Alberto Arias Prieto (Head of the Torque laboratory), and Mr. Iván David Betancur Pulido (Head of the Force laboratory) were extremely important to discuss different aspects related to the development of the project from their experience and the current perspective of the Torque laboratory. Furthermore, the backing provided by the co-worker of the different laboratories that supported part of my specific and transversal NIM activities was very important to

complete the developed project, as well as their different pieces of advice and standpoints, before and during the visit.

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