Toward DEMO Power Plant Concept Selection Under Epistemic Uncertainty

Enrique Miralles-Dolz, Alexander Pearce, James Morris, and Edoardo Patelli

***Abstract*— To make informed decisions during the concept selection activities of a nuclear fusion power plant, it is necessary to evaluate the impact of uncertainties on the feasibility and performance of each concept. A framework for uncertainty quantification and sensitivity analysis has been developed for the PROCESS systems code to allow the direct comparison of different DEMOnstration power plant (DEMO) power plant concepts. To account for epistemic uncertainty, the uncertainty quantification was based on interval analysis, where only the bounds of the interval have to be assumed for each uncertain parameter, and the uncertainty was propagated with Monte Carlo and Latin hypercube sampling. The sensitivity analysis was based on the pinching method, consisting of reducing the interval uncertainty of each input parameter to a baseline point one by one and measuring the uncertainty reduction in the output interval. Its application is shown using the European H-mode DEMO baseline as a use case. Results suggest that the thermal He-4 fraction in plasma, plasma elongation, and H-factor should be examined further to reduce risks on its feasibility.**

***Index Terms*— DEMOnstration power plant (DEMO), nuclear fusion, PROCESS, sensitivity analysis, uncertainty quantification.**

I. INTRODUCTION

DESPITE having built successful fusion reactors in the past, the design and development of a fusion power plant present an unparalleled challenge since it is technically and economically prohibitive to build and test every single concept that is under investigation. However, digital models can help to mitigate this problem. With the recent advances in computer-aided modeling, now, it is possible to build virtual prototypes to study and assess concepts before turning them into a reality. Fusion systems codes, such as PROCESS [1], [2], serve as a tool to perform the initial approach toward a fusion power plant concept, helping to evaluate its performance before narrowing down its operational space with more detailed and sophisticated codes [3].

With uncertainty quantification methods, it is possible to determine outcomes from a concept when some aspects of it are unknown. This application is particularly useful to quantitatively assess concept choices early in the design process and identify areas with high impact on the performance of the concept of choice that needs further development to meet the requirements or could pose a risk for finding a successful concept. Some previous work has been carried out in uncertainty quantification with PROCESS; on the European DEMOnstration power plant (DEMO) as in [4]–[6], on the China Fusion Engineering Test Reactor (CFETR) design [7], or the HELIcal Advanced Stellarator (HELIAS) 5-B stellarator [8]. This work adopts the technique of interval analysis (see [9], [10]) to describe the uncertainties associated with some parameters of the European H-mode DEMO baseline, allowing a wider exploration of their impact on the uncertainty of its major radius and feasibility. This work also provides a framework for uncertainty quantification and sensitivity analysis, which can be used during the DEMO concept selection activities.

For example, for decades, the high confinement, or H-mode, has been considered the preferable plasma operation regime for a fusion power plant [11]. However, after revisiting the potential impact of the type-I edge-localized modes (ELMs) associated with H-mode plasmas, new plasma operational scenarios have been proposed as an alternative [12]. Therefore, to allow comparison among DEMO concepts using different plasma scenarios, it is of paramount importance to design methodologies and metrics that help in the following:

1) to assess how the current state of knowledge affects to each DEMO concept;
2) to identify which areas of knowledge are required to be sharpened to make different DEMO concepts successful.

II. UNCERTAINTY

There are two kinds of uncertainties: aleatory and epistemic. If the distribution function of a random variable is perfectly known, then the stochastic nature of the random variable is fully captured by this distribution function, and the uncertainty is said to be aleatory—it is random by nature. However, when the distribution function cannot be precisely defined, because the information available (e.g., data) does not allow it, then this imprecision is called epistemic uncertainty, which arises from a lack of knowledge about that random variable, and therefore, it should be reducible with additional information.

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Despite there is a long-lasting debate on how to model imprecision [13], [14], the framework developed in this work used intervals to model epistemic uncertainties since the DEMO design parameters are not stochastic by nature, but uncertain. Intervals represent the least amount of useful knowledge since only the bounds of the interval have to be assumed for each uncertain parameter. It is important to note that, even though some of the parameters considered in this work can have fixed values (and, therefore, not being uncertain anymore), making this choice would not be reliable given the lack of evidence about what will be reasonably achievable for the European DEMO. For example, a fusion reactor can be designed to operate with a certain plasma elongation, yet, for the 2015 European H-mode DEMO, it was found that the maximum acceptable plasma elongations (at 95% flux surface) regarding vertical stability in the ramp-down and flat top phases were 1.59 and 1.71, respectively, [15]. Which value of plasma elongation to use for the design of the device is an important question since there could exist better vertical stability measures in the future helping to raise the 1.59 limit, but, at the same time, it would be recommended to be conservative about the 1.71 upper limit since certain plasma instabilities can reduce the vertical stability. The answer to that question is, therefore, subordinated to the technology and knowledge available at the time of design and construction of the European DEMO [16], [17], and using intervals to describe the uncertainty of the plasma elongation takes it into account. However, regardless of the possible differences in nature between design parameters and uncertain parameters, intervals equally capture both design space and epistemic uncertainty, making no difference on the modeling and computational analysis. In any case, modeling design parameters using intervals also helps to find the feasible design space, as shown in this work.

Only six parameters were considered for this work, yet it is possible to increase this number in exchange for a greater computational cost. Sensitivity analysis will help to refine the parameter selection, aiding to discard those parameters that have little or no impact on the uncertainty of the output. The parameters chosen were related to the physics in PROCESS rather than technological (such as efficiencies), as the next step attempts to understand how these uncertainties impact on the different plasma scenarios. To maintain similarity with previous studies, these parameters are present in [6] and are given as follows.

1) *H-Factor* ∈ *[1.0, 1.3]:* The ratio between measured energy confinement time and the predicted energy confinement time by the ITERH-98P(y,2) scaling law [18]. Values greater than 1.3 are not expected to be achievable [19].
2) *Divertor Operational Limit* ∈ *[8.7, 9.5] (MWT/m):* The maximum power allowed to cross the separatrix and flow on the divertor plates, calculated as $((P_{\text{sep}}B_T)/qAR_0)$, where P_{sep} is the power crossing the separatrix, B_T the vacuum toroidal field in the plasma, q the safety factor at the plasma edge, A the aspect ratio, and R_0 the major radius. It is unknown what will be the limit at the time of construction of DEMO, but current concepts aim for ~9.2 (MWT/m) [17].

TABLE I

PARAMETERS USED FOR THE ANALYSIS WITH THEIR ASSOCIATED UNCERTAINTY IN THE FORM OF INTERVAL AND BASELINE VALUE

Parameter	Lower bound	Upper bound	Baseline
H-factor	1.0	1.3	1.1
Divertor Limit (MWT/m)	8.7	9.5	9.2
Core Radius	0.6	0.8	0.75
W Impurity	10^{-5}	10^{-4}	50^{-5}
Plasma Elongation	1.75	1.90	1.85
Thermal He-4 fraction	0.06	0.12	0.069

3) *Core Radius Energy Confinement Time Scaling* ∈ *[0.6, 0.8]:* The energy confinement scaling law has been derived from experiments with low radiation (i.e., without significant radiation inside the separatrix). DEMO is expected to operate with high radiation scenarios [20], and the parameter representing the fraction of radiation that is released from the core has to be adjusted accordingly.
4) *Tungsten Impurity Fraction* ∈ *[10^{-5}, 10^{-4}]:* High-Z impurities generated from the interaction of plasma with plasma facing components lead to losses in energy confinement time due to radiative processes. The amount of tungsten concentration in DEMO during operation is still uncertain, and it is unknown how these impurities will be removed.
5) *Plasma Elongation at the Separatrix* ∈ *[1.75, 1.90]:* Elongation is the dominant plasma parameter and has been reported as having the largest impact on the net electric power of the machine [6]. In conventional tokamaks, an elongation of over 2 is not expected to be controllable, and an elongation smaller than 1.70 could yield poor performances [16]. The current limitations in vertical stability knowledge and technology are the main drivers of uncertainty for the plasma elongation [16], [17].
6) *Thermal He-4 Fraction* ∈ *[0.06, 0.12]:* Helium-4 is one of the products of the Deuterium-Tritium (DT) fusion reaction, and it is a positively charged particle intended to stay confined in the plasma, so its energy can heat the plasma and sustain the fusion reactions, minimizing the amount of external heating required. However, too high a concentration of Helium-4 in the plasma could dilute the fuel and diminish the fusion power; therefore, an optimal solution must exist where both Helium-4 confinement time and fusion power conditions are satisfied. This fraction is highly variable in current transport simulations, and most of the plasma physics experiments were conducted without these ions, so the fraction of it in DEMO plasmas is uncertain.

The uncertain input parameters with their respective intervals and baseline values are summarized in Table I.

III. METHODS

The proposed methodology is based on interval analysis [10], consisting of defining the uncertain parameters as intervals and performing the model simulation to find the minimum and maximum of the output. Due to the size and complexity of PROCESS, this analysis cannot be performed via intrusive methods (i.e., implementing interval arithmetic in the code), which would provide the rigorous output interval.

Fortunately, PROCESS is built with 0–1-D models and, therefore, runs relatively fast (e.g., a single PROCESS run finishes in a few seconds on an ordinary laptop). For this reason, sampling (also called brute-force search) was chosen as the method to obtain the output interval. Also, sampling allows the identification of trends or patterns (such as nonlinearities, discontinuities, and dependencies) in the data, which can be useful to perform sensitivity analysis. For this work, the European H-mode DEMO baseline is modeled in PROCESS, set to minimize the major radius (R_0) constrained with at least 400 MW of net electric power and a pulselength of 2 h.

Uncertainty quantification should be accompanied by a sensitivity analysis because analysts and decision-makers are interested not only in the amount of uncertainty on the model output but also on how do the input parameters uncertainties affect it. Two different approaches were taken to perform sensitivity analysis: one qualitative, visualizing the scatterplots generated with the data previously used to perform uncertainty quantification [21], and one quantitative, based on the pinching method, consisting of reducing the interval uncertainty of each input parameter to a baseline point one by one, and measuring the uncertainty reduction in the output interval [22].

A. Uncertainty Quantification

Major radius (R_0) was chosen as the model output of interest, as it is one of the main drivers of the power plant size, an indicator of cost, and overall feasibility. It would be desirable to have the major radius interval as narrow as possible, which would mean that, for the given input parameters uncertainties, the size of the machine is definite. For example, assuming that the maximum major radius permitted is 12 m, then, if the major radius interval of a specific DEMO concept is [12.3, 12.4] m, then it would be sensible to classify that concept as unfeasible since its major radius would be too large. On the other hand, if the major radius interval is [8.5, 8.6] m, then that concept should be considered a feasible option since its major radius will always be under 12 m.

Worst case scenario happens when the major radius interval is too wide to make a decision, as [8.5, 12.4] m would be. In this case, for the given values of the uncertain input parameters, the major radius could be any within that interval, and therefore, one could not classify that concept as feasible or unfeasible. However, a wide interval is not necessarily a bad result; it means that it is required to reduce the amount of uncertainty in input parameters to be able to make a decision.

For the DEMO concept selection, the distance of the major radius interval ($b - a$ where $R_0 \in [a, b]$) is used as a concept robustness metric, meaning that the smaller the distance is, the more robust the concept results (i.e., the input parameters uncertainties have less impact on the size uncertainty of the reactor).

The sampling method chosen to perform the analysis was Latin hypercube sampling (LHS), which is generally recommended in the literature, as it stratifies over the range of each interval input, making it possible to perform both uncertainty and sensitivity analysis [21].

In LHS, the distribution function of each input parameter X_k is equally divided N times with the same marginal probability $1/N$, where N is the number of desired samples. This division will ensure that the distribution function is properly sampled, as it will avoid repetition of points or missing regions of the function. Then, the algorithm takes only one sample from each division and repeats the process for all the input parameters to later ensemble randomly the taken samples and form the input sets. For this analysis, 6600 samples were employed, which are enough to cover the whole parameter space [23].

It is important to recall that, in order to generate the samples of the uncertain input parameters, LHS requires assuming a probability density function. A uniform distribution was chosen for the uncertain input parameters, with the range being equal to their respective interval, since this distribution stratifies equally through the whole interval, and no preference is given to any region of the interval. However, this step is only required for the sampling, and no probabilistic interpretation should be drawn from the analysis since it would be an artifact of the sampling.

B. Sensitivity Analysis

The objective of the sensitivity analysis is to study how the uncertainty in the output of a model is influenced by the uncertainties of its inputs. Its application in concept selection studies is twofold:

1) In the presence of different DEMO concepts, clarify how parameter uncertainty affects the confidence in the outcome of each concept.
2) Identify parameters that would require resources invested to reduce uncertainty and achieve a suitable degree of confidence in each concept.

Two model outputs were analyzed for this work: major radius and feasibility. The PROCESS systems code has an output variable, which describes whether PROCESS found a feasible solution or not. PROCESS returns a feasible solution when, for a given set of input variables and parameters, all the model constraints are fulfilled. However, if PROCESS cannot find a solution with all the model constraints fulfilled, then it returns the run as unfeasible. This metric is particularly interesting because it can help to identify operational regions that could be problematic to integrate or cannot be achieved.

When the uncertainty on the output of the model has been calculated using sampling methods, the simplest procedure to perform sensitivity analysis is examining the scatterplots associated with the input parameters and the model output [21]. In case a parameter has a significant effect on the major radius, then it should show a discernible pattern on its corresponding scatterplot. These plots have been accompanied by a weighted linear regression to help visualize trends in data.

To enhance the robustness of the suggestions of the scatterplots, a more quantitative method for local sensitivity analysis based on value-of-information is also carried out [24].

TABLE II

RESULTS OF MAJOR RADIUS UNCERTAINTY QUANTIFICATION

Major Radius	metres
Minimum:	7.929
Maximum:	10.322
Distance:	2.393

Its objective is to measure the reduction of uncertainty on the output if extra knowledge about the inputs is acquired. The initial step is to calculate the output uncertainty with all the input parameters being uncertain (as in the section before). Then, it follows a process called *pinching*, consisting of reducing the uncertainty of each input parameter to a baseline value, and comparing the uncertainty on the output before and after performing pinching for that parameter [22]. The score for each parameter k is calculated as

$$\text{Score}_k = 1 - \frac{\text{Distance}(R_0)_k}{\text{Distance}(R_0)_{\text{Total}}} \tag{1}$$

where $\text{Distance}(R_0)_k$ is the width of the major radius output interval when uncertainty in parameter k has been reduced to a baseline point keeping all the other parameters uncertain, and $\text{Distance}(R_0)_{\text{Total}}$ is the width of the major radius output interval when all the input parameters are uncertain. The greater the score is, the greater the impact of that parameter on the output uncertainty.

Finally, data were classified into two categories: feasible and unfeasible. The dependence of the feasibility with the different parameters is visualized with density functions, aiding the identification of the parameter space regions with a higher or lower density of feasible samples (as shown in Fig. 4).

IV. RESULTS

Results of the impact of parameters uncertainty on the major radius of the European H-mode DEMO baseline are summarized in Table II. The results suggest that, given the current state of the knowledge about the parameters employed for this study, the maximum length that the baseline can deviate from the predictions is 2.393 m.

The current estimation for the major radius of the European H-mode DEMO baseline is 9.0 m [12], which is inside the predicted interval of [7.929, 10.322] m. However, values greater than 9.0 m are also predicted considering design uncertainties, meaning that there is a possibility of DEMO being larger than currently estimated.

Visualizing the scatterplots, the major radius showed strong dependence on the H-factor (see Fig. 1), plasma elongation (see Fig. 2), and thermal He-4 fraction (see Fig. 3), suggesting that, in this analysis, these are the parameters with the highest impact on the major radius uncertainty inside PROCESS. When these parameters are uncertain, the operational divertor limit, core radius, and tungsten impurity fraction seem to have little impact on the major radius uncertainty.

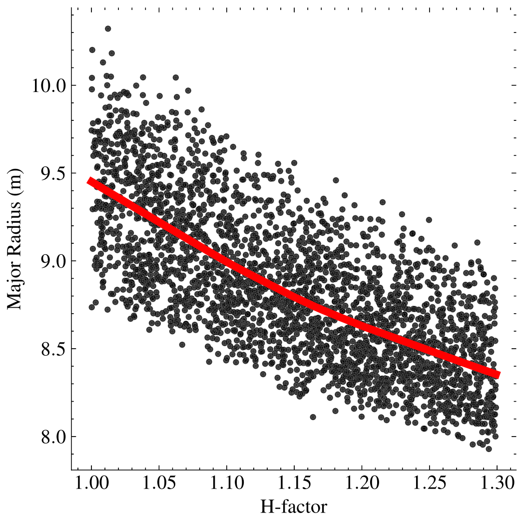

Fig. 1. Scatterplot of major radius against H-factor. Black line is a locally weighted linear regression to help with the trend visualization.

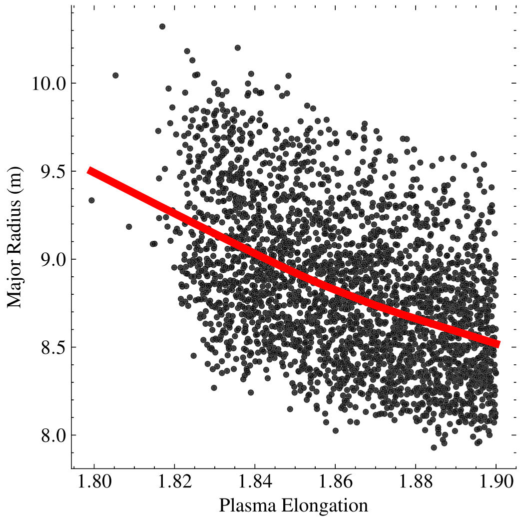

Fig. 2. Scatterplot of major radius against plasma elongation. The missing data for values of plasma elongation ≤1.80 are due to the fact that PROCESS was unable to find feasible solutions in that parameter space.

TABLE III

REDUCTION OF MAJOR RADIUS UNCERTAINTY AFTER PINCHING EACH CORRESPONDING PARAMETER TO ITS BASELINE VALUE, CALCULATED AS IN (1)

Parameter	Uncertainty Reduction
Thermal He-4 Fraction	0.3935
H-factor	0.2766
Plasma Elongation	0.1647
W Impurity Fraction	0.1130
Core Radius	0.0186
Divertor Limit	0.0075

The results suggested by the scatterplots are confirmed by the pinching sensitivity analysis, which results are summarized in Table III. Reducing thermal He-4 fraction uncertainty to its baseline point would reduce the major radius uncertainty 39.35%, while reducing divertor limit uncertainty would return a negligible reduction of 0.75%.

Feasibility space shows the highest dependence with the plasma elongation and the thermal He-4 fraction. The diagonal (top left, bottom right) of Fig. 4 shows the feasibility

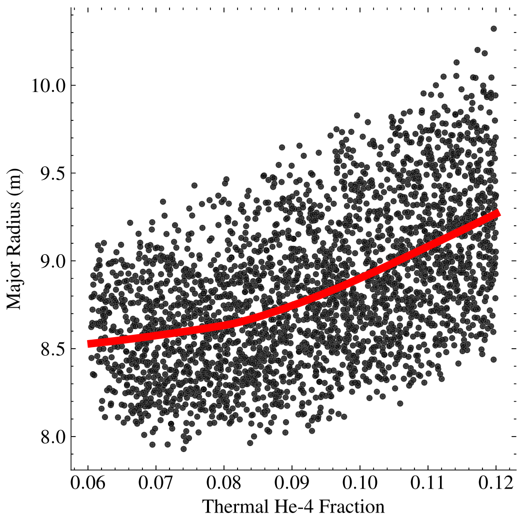

Fig. 3. Scatterplot of major radius against thermal He-4 fraction.

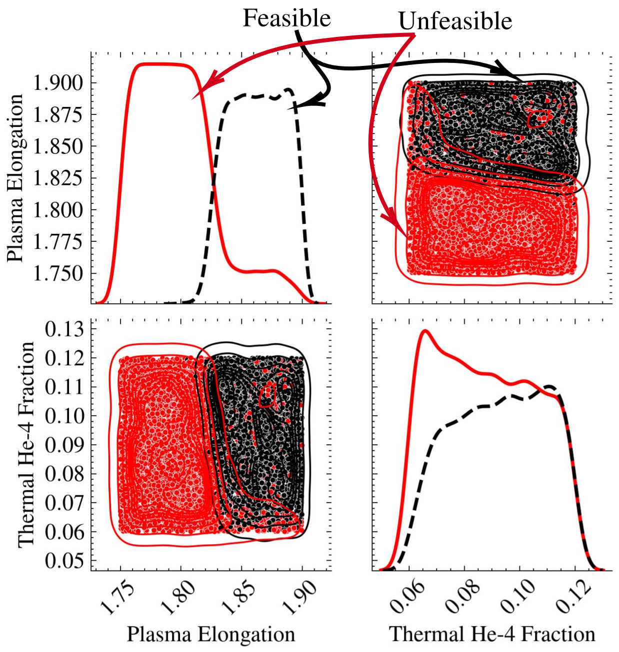

Fig. 4. Density plots (diagonal) and scatterplots (top right and bottom left) of the plasma elongation and thermal He-4 fraction showing the distribution of the proportion of feasible and unfeasible samples.

distributions of the samples for the plasma elongation and thermal He-4 fraction, respectively. The plasma elongation manifests a feasibility threshold of around 1.83, as it shows a steep increase of feasible samples and decrease of unfeasible samples around that value. On the other hand, the thermal He-4 fraction shows a linear increase in feasibility. These results may indicate that the plasma elongation should be at least 1.83 to fulfill the net electric power output constraint of 400 MW, and greater concentrations of thermal He-4 in the plasma are favorable to achieve the pulselength constraint of 2 h. In fact, it has been shown that greater fusion power is associated with larger elongations [6], and He-4 contributes to increase the energy confinement time when it does not exceed the dilution upper limit [25]. To visualize the combination effects on the feasibility space, the scatterplots of the plasma elongation against the thermal He-4 fraction are displayed on the top right and bottom left figures of Fig. 4. It is possible to discern a small region of unfeasible samples when the elongation is around 1.88 and the thermal He-4 fraction around 0.11, which could indicate that PROCESS is not finding feasible solutions for certain combinations of the parameter values around that region of the parameter space. However, this conclusion should be carefully inspected since it could be caused by the combinations of other parameters that remained unnoticed.

V. CONCLUSION

This is the first work on epistemic uncertainty propagation in the form of intervals using PROCESS. The objective was to develop the methodology and computational tools required to compare the impact of uncertainty on different DEMO concepts and the European H-mode DEMO baseline served as the use case. The resources developed for this work can be helpful to identify areas with significant impact on the uncertainty of fusion power plants and provide information during DEMO concept design and selection.

In the case of the European H-mode DEMO baseline, we found that H-factor, plasma elongation, and thermal He-4 fraction had the largest impact on the uncertainty of the major radius and the PROCESS feasibility, given the parameter space explored.

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