Sensitivity Analysis of Capital Cost of European DEMO Design

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***Abstract*— Conceptual designs for a European demonstration (EU-DEMO) power plant are based on extrapolations of physics scaling laws and current understanding of engineering limits based on available technologies. It is imperative to quantify the impact of uncertainties in physics and engineering parameters on the ability to produce an economically attractive future fusion power plant that meets key design outcomes. In this work, the sensitivity of the expected capital cost of an EU-DEMO power plant has been studied using the systems code PROCESS. A systems code aims to model interactions between subsystems of a fusion power plant and provide consistent solution across a large parameter space. The PROCESS system code allows for user-defined initial conditions and constraints and then optimizes using a given figure of merit to find optimal design parameters. We present a sensitivity analysis on optimizations around the 2018 pulsed EU-DEMO baseline, and this allows for the identification of the most consequential model parameters and the magnitude of the nonlinear interactions between them. We consider the pulsed EU-DEMO baseline, and while fixing the major radius and optimizing for fusion gain Q, we present a sensitivity analysis of the role of the physics and engineering parameters and constraints in determining the capital cost of such a device. We identify the dominant physics parameter as the power threshold necessary to enter H-mode, which accounts for 45% of the sensitivity and find high interactions between plasma shaping parameters and other power plant subsystems. This analysis allows for the identification of areas of additional technical focus and uncertainty propagation.**

***Index Terms*— Costing, demonstration (DEMO), PROCESS, sensitivity analysis, uncertainty quantification.**

I. Introduction

THE European demonstration (EU-DEMO) program aims to design and build a DEMO fusion power plant by the 2050s [1]. For the program to meet its aims of demonstrating the use of fusion power as an attractive source of electricity, the cost of a power plant must play a central role in the determination of the design. To fully explore the conceptual design space for such a fusion device, it is important to explore the role uncertainties of plasma physics parameters and engineering constraints on the capital cost of an EU-DEMO device. This will act as an aid in the selection of technologies and give understanding for the trade-offs between performance and cost considerations.

These integrated design problems, which span a large parameter space, are investigated with systems codes, such as PROCESS [2], [3]. A systems code includes 0-D and 1-D physics and engineering models for all important fusion power plant subsystems, which allows for finding a self-consistent solution while optimizing for some figure of merit, for example, minimal major radius R_0 or maximum fusion gain Q. The PROCESS systems code is also coupled to a costing model that produces an estimate for the capital cost of the machine.

The PROCESS systems code is able to be run very fast, on the order of seconds on a typical laptop; therefore, it is ideally suited to be used for uncertainty quantification and sensitivity analysis. This refers to a set of techniques where model input is varied to study their effect on model output, allowing for the investigation of performance sensitivity and margins in a given design point. Uncertainty quantification has been performed using PROCESS previously to study the sensitivity of DEMO machine performance to physics and engineering parameters [4], [5], [6]. In addition, in the literature, there have been studies on ITER and DEMO with the SYCOMORE systems code [7] and costing sensitivity analysis of a proposed compact pilot plant [8].

In this work, we will use a number of sensitivity analysis techniques to investigate the influence of physics and engineering parameters on DEMO capital cost. To do this, we have implemented two new uncertainty tools into the PROCESS systems code and have used them to perform an analysis of the capital cost of a DEMO machine. This study introduces the use of the method of elementary effects and the Sobol technique into the PROCESS systems code [9], [10]. The first of these is a computationally inexpensive technique that allows for the ranking of model input parameters on their influence on the model solution, while the second is a variance-based technique, which allows for the investigation of interactions between model parameters. Together, these new techniques will allow for a detailed investigation of the design space trade-offs between physics and engineering performance and machine capital cost.

In many energy projects, the levelized cost of electricity is used as a metric of its economic competitiveness. EU-DEMO aims to be a DEMO of an integrated solution for a fusion

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TABLE I

LIST OF PARAMETERS CONSIDERED IN THE SENSITIVITY ANALYSES IN THIS WORK AND THEIR PESSIMISTIC AND OPTIMISTIC SCENARIOS. THE MOTIVATION FOR THE UPPER AND LOWER LIMITS USED IN THIS STUDY HAS BEEN DISCUSSED IN THE PREVIOUS DEMO SYSTEMS CODE UNCERTAINTY STUDIES [4], [5], [6]

Parameter	Lower Limit	Upper Limit
$f_{\rm GW}^{\rm max}$ Maximum allowed line averaged electron density in fraction of Greenwald Density	1.1	1.3
$H_{98,y2}$ Radiation corrected H-factor	1.0	1.2
$\rho_{\rm core}$ Normalised radius defining the core plasma region	0.45	0.75
f_{He} Helium impurity fraction	0.085	0.115
f_W Tungsten impurity fraction	10^{-5}	10^{-4}
Maximum ratio of $P_{\rm sep}B_T/qAR$	8.7 MWTm^{-1}	9.7 MWTm^{-1}
$f_{\rm LH}^{\rm min}$ Lower bound LH Threshold	0.85	1.15
$c_{\rm BS}$ Bootstrap current coefficient	0.95	1.05
$\Gamma_{\rm rad}^{\rm max}$ Radiation Peaking Factor	2.0	3.5
$\kappa_{\rm sep}$ Plasma elongation	1.8	1.9
$\eta_{\rm ECRH}$ ECRH wall plug efficiency	0.3	0.5
$f_{\rm CD}$ Current drive efficiency factor	0.5	5.0
$\eta_{\rm th}$ Thermal to electric conversion efficiency	0.36	0.4
$\eta_{\rm iso}$ Isentropic efficiency of first wall and blanket coolant pumps	0.75	0.95
$q_{95}^{\rm min}$ Lower bound	3.25	3.75
$P_{\rm inj}^{\rm max}$ Maximum allowed injected power	51 MW	61 MW
$\sigma_{\rm CS}^{\rm max}$ Allowed Hoop Stress in CS structural material	600 MPa	720 MPa
$\sigma_{\rm TF}^{\rm max}$ Allowed Tresca in TF coil structural material	520 MPa	640 MPa
A Aspect Ratio	3.0	3.2
$B_T^{\rm max}$ Maximum Toroidal Field	11T	12T
$\delta_{\rm sep}$ Triangularity	0.4	0.6

power station and as a first of a kind reactor may have a high cost of electricity. Therefore, in this work, we focus on the capital cost and leave the problem of optimizing the levelized cost of electricity to the generation of commercial power plant after EU-DEMO.

The structure of this article will be as follows. First, we will perform a set of single parameter evaluations and present tornado plots of DEMO cost sensitivities to physics and engineering parameters. Then, in Section III, we will briefly introduce and use the method of elementary effects and discuss its uses in ranking cost drivers. In Section IV, the Sobol technique will be introduced and used to analyze the PROCESS DEMO cost model, and finally, Section V provides a summary and outlook.

II. Single Parameter Evaluations

We identify the physics and engineering parameters, which may be strong drivers of the total capital cost. First, we consider the physics and engineering parameters that have been used in the previous uncertainty analysis of PROCESS [4], [5], [6], but then, we have also widened the scope of the parameters considered. In Table I, we list all PROCESS parameters considered in this study and what we consider the optimistic and pessimistic scenarios.

As the PROCESS model involves a nonlinear optimization procedure, the behavior and sensitivity of the model are heavily influenced by the choice of figure of merit. Therefore, throughout this study, we will consider two different cases, first optimizing the 2018 baseline for smallest major radius R_0 and, second, considering the 2018 baseline with fixed major radius R_0 optimizing for maximum fusion gain Q [11].

To gain an understanding of the sensitivity of parameters on the machine capital cost, we first consider a one-at-a-time analysis comparing the relative changes in capital cost. Using the 2018 baseline, we consider each parameter listed in Table I, in turn, evaluating the 2018 baseline but with the parameter changed to either its optimistic or pessimistic limits. To aid in finding feasible solutions, we consider the requirement of solutions with at least $P_{\rm net,el} = 400$ MW and a pulselength of $t_{\rm pulse} = 2$ h.

In Fig. 1, we present tornado plots summarizing this analysis, where the parameters are ranked in relative change in capital cost. Fig. 1(a) shows the results for DEMO when optimizing the major radius R_0. We observe that the most influential parameter is the upper limit of the electron density expressed in units of the Greenwald density $f_{\rm GW}$. Between the range of $f_{\rm GW} = 1.3$ in the optimistic case to $f_{\rm GW} = 1.1$ in the pessimistic case where the capital cost increases from 94.6% to 108.0% of the baseline capital cost between these scenarios.

After the upper limit of the electron density, the next most important PROCESS parameters in this model are the H-factor $H_{98,y2}$, the lower bound plasma safety factor, and the plasma elongation and triangularity. We also observe that the PROCESS parameters, which influence the balance of plant considerations, the thermal efficiency, the electron cyclotron resonance heating (ECRH) wall plug efficiency, and isentropic efficiency of the first wall and blankets, have strong influences on the capital cost. This can be explained as a higher efficiency of the balance of plant parameters, means that the less fusion power is required to meet the net electric constraints. This allows for smaller plasma volume, which, in turn, allows for a smaller machine.

In all cases, the PROCESS optimization procedure finds a solution operating safely above the LH threshold, where $P_{\rm LH} \simeq 1.2 P_{\rm sep}$ [12]. In addition, we also find that the divertor protection parameter of the ratio $P_{\rm sep}B_T/qAR$ is not dominant in determining the capital cost. The smallest major radius solution in this set of PROCESS runs is $R_0 = 8.42$ m, and therefore, at this size, only impurity seeding of Argon is required to meet the divertor heat flux constraints in agreement with other studies on divertor protection [13].

In Fig. 1(b), we present the tornado plot for DEMO optimized for maximum fusion gain Q. Notably, we find different parameters, which are the drivers of the capital cost with the leading effect arising from the LH threshold, where for $f_{\rm LH} = 0.85$, we have a capital cost of 111.7% of the baseline capital cost, while for $f_{\rm LH} = 1.15$, we find a solution with 91.5% the baseline capital cost. It is counter intuitive that reducing the LH threshold causes PROCESS to optimize Q for a solution with higher a capital cost, but with a lower $f_{\rm LH}$ and a higher Q solution is found, which demands larger magnetic fields and larger plasma currents. A summary of the key differences in the plasma physics scenarios is shown in Table II and indicates that the magnetic field on axis correlates well with the machine capital cost.

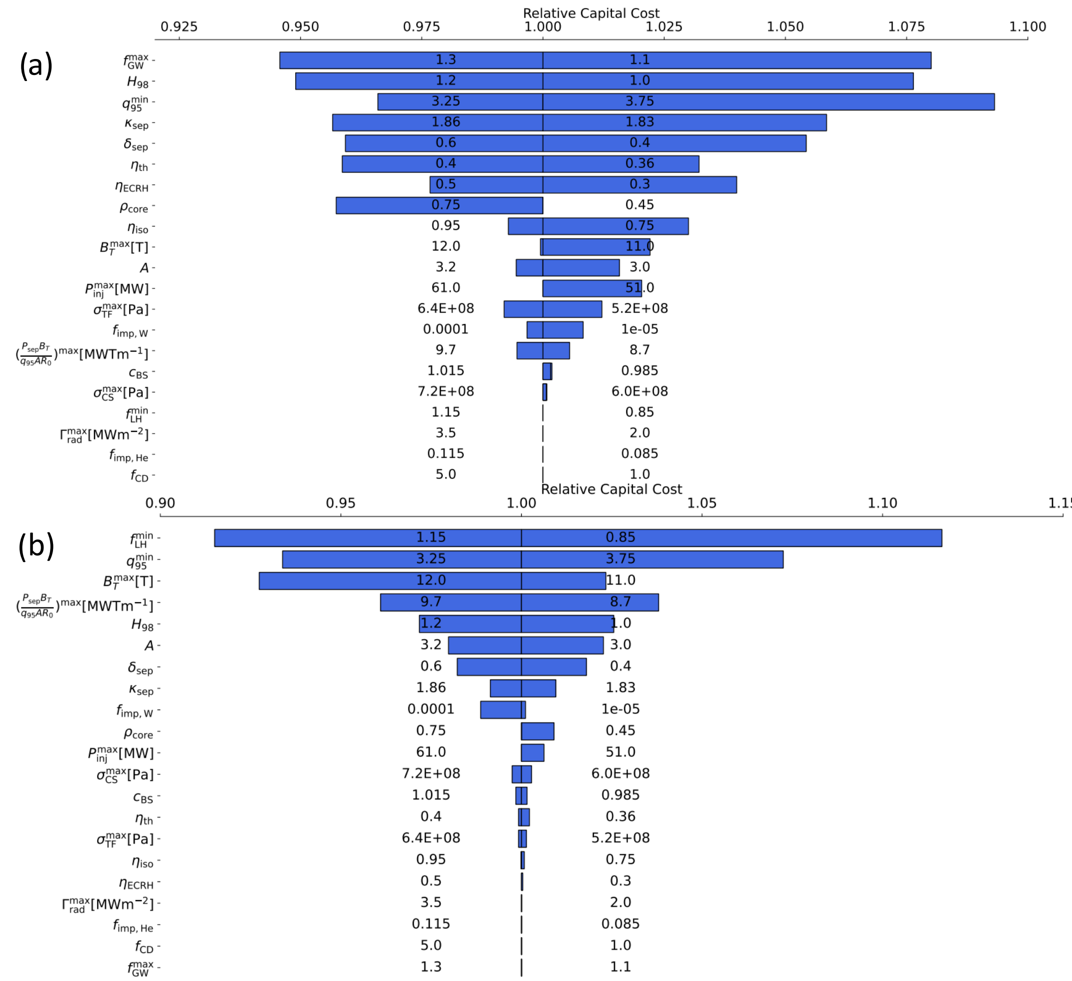

Fig. 1. (a) Tornado plot for EU-DEMO 2018 baseline optimizing for minimal major radius. (b) Tornado plot for EU-DEMO 2018 baseline optimizing for maximum fusion gain Q. The numbers placed on the left and right of the vertical bars in these charts denote the optimistic and pessimistic values of these variables used in this study.

TABLE II

PLASMA SCENARIO PARAMETERS FOUND BY PROCESS WITH OPTIMISTIC AND PESSIMISTIC LH THRESHOLDS OPTIMIZING FOR MAXIMUM FUSION GAIN Q

f_{LH}	$B_T\,(R_0)$	I_p	$\bar{n}_{20}$	f_{GW}	Q	Capital Cost
0.85	$7.42T$	$25.49MA$	0.77	0.84	42.78	111.68%
1.15	$6.54T$	$22.47MA$	0.68	0.84	34.9	91.46%

After the LH threshold, the highest ranked PROCESS parameters in Fig. 1(b) are the lower bound plasma safety factor and the maximum peak toroidal field. When optimizing the DEMO 2018 baseline for the maximum fusion gain, PROCESS consistently finds solutions in the high magnetic field and high plasma current regime with $B_T(R_0) > 6T$ and $I_p > 22MA$, and where P_{sep} is minimal for H-mode operation, satisfying $P_{\text{LH}} = P_{\text{sep}}$. Because of the fixed radial build, this sets strong constraints on the parameter space explored as the Martin scaling for the LH threshold [12] reduced to a function of on axis toroidal field and density $P_{\text{LH}} \approx n_{20}^{0.717} B_T^{0.803}$. In this scenario, the design of magnets, which influences the magnetic energy in the plasma, is the largest underlying driver of cost. In contrast to the case where we minimize the major radius, we no longer see a strong influence of balance of plant parameters due to the fixed radial build.

We must note that the magnitude of the change in capital cost seen in the tornado plots in Fig. 1 can be caused by two factors, the sensitivity of the capital cost on that parameter and the size of the range between upper and lower limits considered. Therefore, while the approach used to make the tornado plot gives a good approximate ranking of capital cost sensitivity to the parameter considered, it cannot disentangle these competing effects. For a more robust sensitivity measure, we will aim to implement the variance-based Sobol technique, while this method, which will be explained in Section IV, has several benefits, it has one clear drawback, that is computationally expensive. Therefore, first, we must utilize a parameter screening technique called the method of elementary effects or the Morris method, which we will describe in Section III to identify the key parameters to focus our analysis upon.

III. METHOD OF ELEMENTARY EFFECTS

The method of elementary effects, which is also known as the Morris method, is a sensitivity measure for ranking the parameters in order of effect on a model output [9]. One key

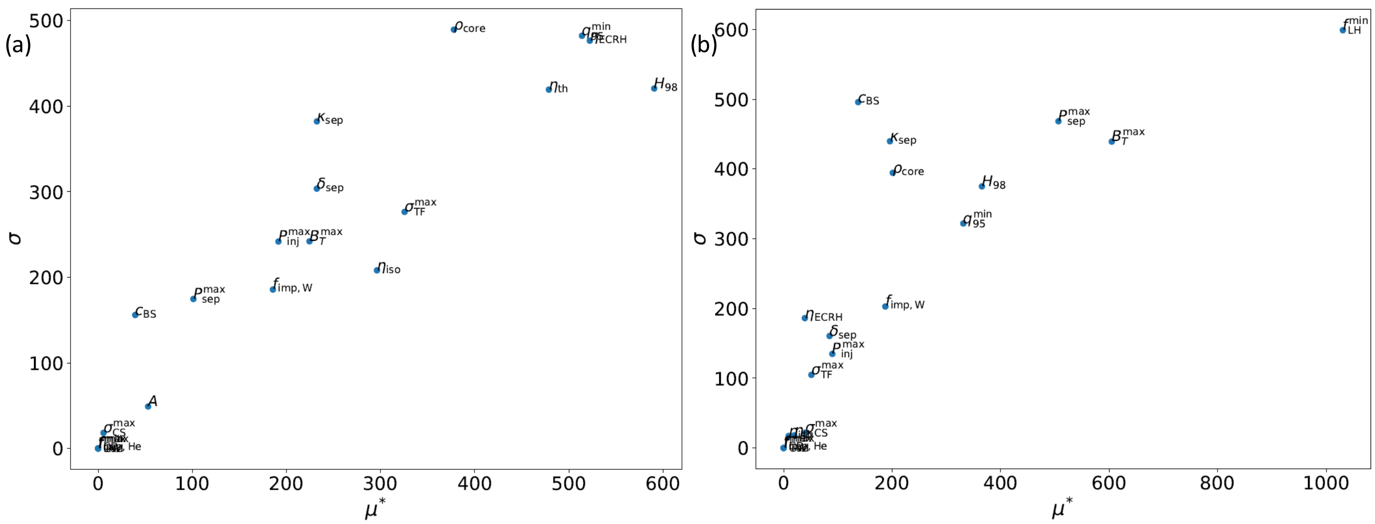

Fig. 2. (a) Scatter plot showing the absolute mean and variance of the elementary effects of PROCESS physics and engineering parameters for EU-DEMO 2018 baseline optimized by minimizing capital cost. (b) Scatter plot for the absolute mean and variance of the elementary effects of the same PROCESS parameters for EU-DEMO 2018 baseline optimized for maximum fusion gain Q. Both plots have been created using $r = 25$ trajectories. The model parameters, which appear in the top-right sector of these plots, are those which are the most consequential model inputs.

advantage of this method is its relatively inexpensive computationally as compared with variance-based methods. Therefore, this technique is best utilized as a screening method to identify negligible variables and selecting a reduced set of input variables for use in more computationally demanding sensitivity analysis studies. This method has also been discussed in the context of PROCESS in a previous work [14].

We denote the PROCESS model as $y(\mathbf{X})$, where $\mathbf{X} = (X_1, X_2, \ldots, X_k)$ is the ith model input of set of k inputs considered. The input space is then sampled in a k-dimensional hypercube, which has been discretized into p levels. The elementary effects for the model are computed by considering a set of trajectory through the input space, which sample the input space from randomly select initial points. For set of inputs X, the elementary effect of the ith input factor is given by the expression

$$\mathrm{EE}_i^j = \frac{y(\mathbf{X} + \mathbf{e}_i \Delta) - y(\mathbf{X})}{\Delta} \tag{1}$$

where, here, $\mathbf{e}_i$ is the orthonormal basis vector for the ith dimension of the input space hyper cube, and Δ is a level spacing, which is given by $\Delta = p/(2(p-1))$. For more information on this sensitivity measure, see Saltelli *et al.* [10]. This procedure produces j elementary effects for each input variable considered, and we then study the distributions of these computed values along their trajectories. This is done by identifying sensitivity measures using the two expressions

$$\mu_i^* = \frac{1}{r} \sum_{j=1}^{r} \left| \mathrm{EE}_i^j \right| \tag{2}$$

$$\sigma_i^2 = \frac{1}{r-1} \sum_{j=1}^{r} \left(\mathrm{EE}_i^j - \mu_i \right)^2 \tag{3}$$

where μ_i^* is the absolute mean of the elementary effects of the ith parameter, and σ_i is the standard deviation of the elementary effects of the ith model parameter. The absolute mean, shown in (2), can be seen as providing a ranking of the effect of an input on model output, and this allows for easy identification of negligible model inputs, whereas the standard deviation, shown in (3), provides an estimation of the linearity of the model input. This shows that parameter with $\sigma_i \simeq 0$ would indicate a nearly linear parameter, which interacts very weakly with other model inputs in determining the model output.

All samples will be taken with a flat distribution between their upper and lower limits. The same upper and lower limits, as shown in Table I, are used. For both figure of merit cases we have studied, will now take the eight parameters with highest μ_i^* to study with the variance-based technique of Sobol indices.

In Fig. 2(a), we present a scatter plot of the absolute mean and standard deviation of the elementary effects for each parameter for the figure of merit of minimizing capital cost. We expect parameters, which appear in the upper right sector of these plots, to be the most consequential model inputs.

Comparing between optimizing for a minimal major radius and machine capital cost, we see broad agreement in the ranking of the effects on the capital cost. The one extreme outlier is the upper bound of the Greenwald fraction f_{GW}, which in Fig. 1(a) is the most import parameter for determining the capital cost, and Fig. 2(a) shows that it has $\mu^* = 0$, and the reason for this change is currently unclear.

In Fig. 2(b), we present the plot of the absolute mean against the standard deviation of the elementary effects for each parameter, and for a fixed radial build, we use the fusion gain Q as the figure of merit. If we compare the highest absolute means of the elementary effects to the single parameter study shown in Fig. 1(b), the same parameters make up the five most influential, but apart from the lower bound

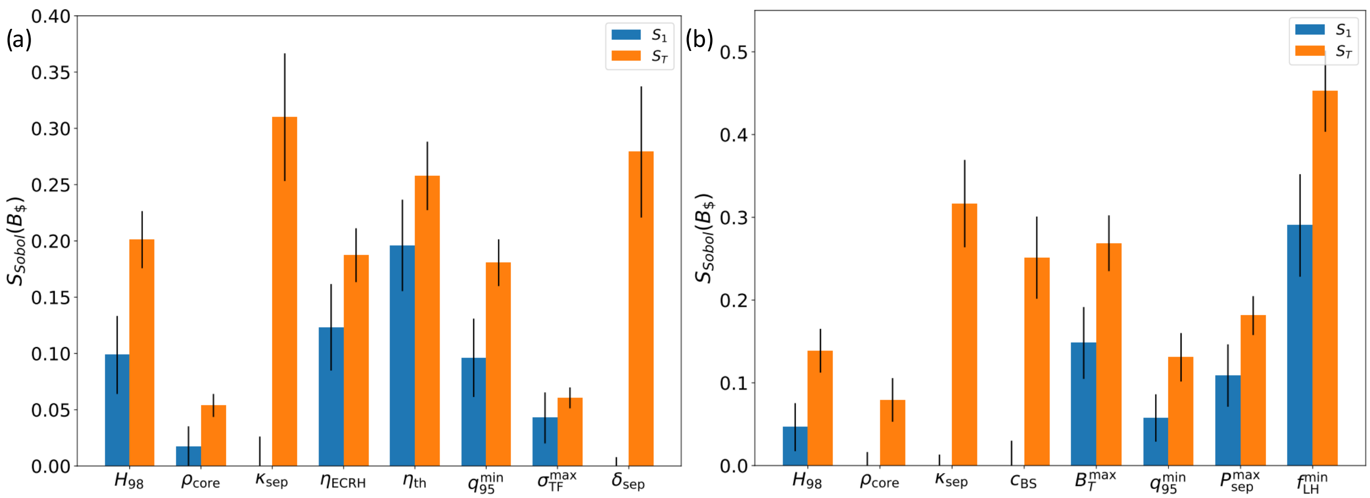

Fig. 3. Here, presented are charts showing the first order S_1 and total S_T Sobol indices of screened PROCESS physics and engineering parameters for EU-DEMO 2018 baseline. (a) Sobol indices for PROCESS when optimized for minimal capital cost. (b) Sobol indices for PROCESS optimized for maximum fusion gain Q.

on the LH threshold being the most important, the order of their ranking is different.

IV. Sobol Method

The Sobol Method is a Monte Carlo-based sensitivity measure that shows the output variance caused by each model input and allows for the investigation of interactions between inputs. The technique is based on the idea of conditional variance $\text{Var}(y|\mathbf{X})$, where the output $y(\mathbf{X})$ variance is obtained by fixing one input of $\mathbf{X}$ to a given value X_i. An input with a greater influence on the model output will produce a smaller expected value of the conditional variance $E_{X_{\sim i}}(\text{Var}(y|X))$ as compared with the total variance $\text{Var}(y)$. The $\mathbf{X}_{\sim i}$ notation here denotes the set of all variables except X_i.

There are two types of Sobol indices we will consider in our study, the first-order Sobol indices $S_{1,i}$ and the total Sobol indices $S_{T,i}$. The first-order indices give the sensitivity measure of the model output due to an input X_i; therefore, it captures the effect of varying X_i alone while averaging over all over model input variations. It can be expressed as

$$S_{1,i} = \frac{\text{Var}\big(E_{X_{\sim i}}(y|\mathbf{X})\big)}{\text{Var}(y)}. \tag{4}$$

As the first order only includes the variance from one input parameter, it only captures linear behavior of the model, and in the case of models that are linear, the first-order indices would be equivalent to linear regression coefficients. The total indices allow for the study of input interactions. Total indices account for the total contribution to the model output variation due to the model input X_i, and it includes the first-order index and all higher order indices arising due to input interactions. They are computed using the expression

$$S_{T,i} = \frac{E_{X_{\sim i}}(\text{Var}(y|X_{\sim i}))}{\text{Var}(y)}. \tag{5}$$

When sampling the input parameter space, we implement the Saltelli sampling. For more information on this sensitivity measure, see Saltelli *et al.* [10].

We present the output of the Sobol analysis for DEMO when we optimize for minimal capital cost in Fig. 3(a). The dominant linear effects are the parameters related to the balance of plant, ECRH wall plug efficiency, and the thermal to electric conversion efficiency, and we also note that their first-order Sobol indices are within the 95% confidence interval for the total Sobol indices, so we infer that their influence on the machine capital cost is nearly completely linear without interactions with other model inputs. In contrast, we find very small first-order indices for the plasma shaping parameters, elongation, and triangularity, but they are the largest total Sobol indices, meaning that the plasma shaping parameters are highly nonlinear and interact with many other model inputs in producing the output capital cost. Indeed, the very high S_T values found for the plasma elongation and triangularity suggest that they interact with all other model inputs. A deeper investigation of these interactions would require the computation of the second Sobol indices, and we do not currently have enough PROCESS runs to achieve acceptable statistical certainly in these indices.

Considering now the case of a fixed radial build and optimizing for fusion gain, the Sobol analysis is presented in Fig. 3(b). We see once again that the lower LH threshold is by far the dominant driver in the capital cost with optimal fusion gain. The second largest first-order Sobol index is the maximum toroidal field, this is again suggestive to the degree that magnets are central to the costing of the machine. The plasma elongation and the bootstrap current coefficient appear to have large contribution to interaction effects but very small linear effects on the model output. We suggest that the input parameter space, which contains some strongly coupled interactions, is caused by the high plasma current regime that PROCESS finds solutions within when optimizing for fusion gain. The high uncertainties in 95% confidence intervals are due to number of runs used and highlight the computational cost of the Sobol technique.

The high Q solutions parameter space can give machines with quite different plasma scenarios to the typical EU-DEMO baseline, and if this is the input space, we want to explore for future device; we must also consider that for safety reasons, there is need to operate in regime well above the LH threshold; therefore, the pessimistic scenario discussed in Section II is worth exploring in more detail.

V. Conclusion

This study suggests, for a design with a fixed major radius, that magnet technologies will be the biggest driver in costs in EU-DEMO. Whereas, for a design with a variable reactor size, a broader selection of physics and engineering drives the cost, with the strongest influences being the balance of plant efficiencies and physics parameters energy confinement time and plasma shaping and edge q-profile parameters. This suggests that the future work understanding the uncertainties in these subsystems will reduce the uncertainties in DEMO design costings.

This work gives a sensitivity analysis of the capital cost of EU-DEMO for uncertainties in physics and engineering solutions, but this is an additional issue of the uncertainties in the costing model itself, which much be addressed in the future for a complete investigation of costing uncertainties. For instance, this analysis assumes a fixed discount rate, 0.06. This extension of the uncertainty analysis would allow for the study of the relative size of the uncertainties arising from either physics and engineering or from the costing model. This will help identify the largest sources of uncertainty in estimates of future power plant capital cost and guide future work. In addition, understanding uncertainties in these parameters is crucial for understanding the viability of reactor designs.

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Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. To obtain further information on the data and models underlying this article, please contact PublicationsManager@ukaea.uk.

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