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Sensitivity Analysis of Capital Cost of European DEMO Design

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Sensitivity Analysis of Capital Cost of European DEMO Design

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***Abstract*—Conceptual designs for a European demonstration power plant (EU-DEMO) 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, this allows for the identification of the most consequential model parameters and the magnitude of the non-linear 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*—DEMO, PROCESS, costing, uncertainty quantification, sensitivity analysis**

I. Introduction

The EU-DEMO program aims to design and build a demonstration 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 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 large parameters space are investigated with systems codes, such as PROCESS[2], [3]. A systems code includes 0D and 1D physics and engineering models for all important fusion power plant subsystems which allows for find a self-consistent solution while optimising for some figure of merit, for example minimal major radius R_0 or maximum fusion gain Q. The PROCESS system 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 run very fast, on the order of seconds on a typical laptop, there for it is ideally suited to be used for uncertainty quantification and sensitivity analysis. This refers to a set of techniques where model input are varied to study their affect 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[5], [4], [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 the method of elementary effects and the Sobol technique into the PROCESS systems code. The first of these is a computationally inexpensive techniques 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.

The structure of this paper will be as follows, first we will perform a 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 analyse 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. Firstly, we consider the physics and engineering parameters that have been used in the previous uncertainty analysis of PROCESS[5], [4], [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.

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

TABLE I

A LIST OF PARAMETERS CONSIDERED IN THE SENSITIVITY ANALYSES IN THIS WORK AND THEIR PESSIMISTIC AND OPTIMISTIC SCENARIOS.

As the PROCESS model involves a nonlinear optimisation procedure the behaviour and sensitivity of the model is heavily influenced by the choice of figure of merit. Therefore, throughout this study we will consider two different cases, firstly optimising the 2018 baseline for smallest major radius R_0 and secondly considering the 2018 baseline with fixed major radius R_0 optimising for maximum fusion gain Q.

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 it's optimistic or pessimistic limits. To aid in finding feasible solutions we consider the requirement of solutions with at least $P_{net} = 400MW$ and pulse length of $t_{pulse} = 2hrs$.

In Fig. 1 we present tornado plots summarising this analysis, where the parameters are ranks in relative change in capital cost. In Fig. 1.a shows the results for DEMO when optimising 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_{GW}. Between the range of $f_{GW} = 1.3$ in the optimistic case to $f_{GW} = 1.1$ 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 is 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 ECRH wall plug efficiency and isentropic efficiency of the first wall and blankets, have strong influences on the capital cost. This is explained by a more efficient balance of plant requires less fusion power to meet the net electric constraints allowing for a smaller machine.

In all cases the PROCESS optimisation procedure finds a solution operating safely above the LH-threshold, where $P_{LH} \simeq 1.2P_{sep}$. In addition, we also find that the divertor protection parameter of the ratio $P_{\text{sep}}B_T/qAR$ is not dominant in determining the capital cost. This smallest major radius solution in this set of PROCESS runs is $R_0 = 8.42m$ 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[9].

In Fig. 1.b we present the tornado plot for DEMO optimised for maximum fusion gain Q, notably we find different parameters which are drivers of the capital cost with dominant effect arising from the LH threshold, where $f_{LH} = 0.85$ we have a capital cost of 111.7% of the baseline capital cost, while for $f_{LH} = 1.15$ we find a solution with 91.5% the baseline capital cost. It is counter intuitive that reducing the LH threshold causes PROCESS of optimise Q for a solution with higher a capital cost, but with a lower f_{LH} 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 magnetic field on axis correlates well with the machine capital cost.

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%

TABLE II

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

After the LH-threshold the highest ranked PROCESS parameters in Fig. 2 are the lower bound plasma safety factor and the maximum peak toroidal field. When optimising the DEMO 2018 baseline for the maximum fusion gain PROCESS consistently finds solution 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 $P_{LH} = P_{sep}$. Because of the fixed radial build this sets strong constraints on the parameter space explored as the Martin scaling for the LH-threshold[10] reduced to a function of on axis toroidal field and density $P_{LH} \sim n_{20}^{0.717}B_T^{0.803}$. In this scenario the design of magnets which influences the magnetic energy in the plasma is the largest underling driver of cost. In contrast to the case where we minimise the major radius, we

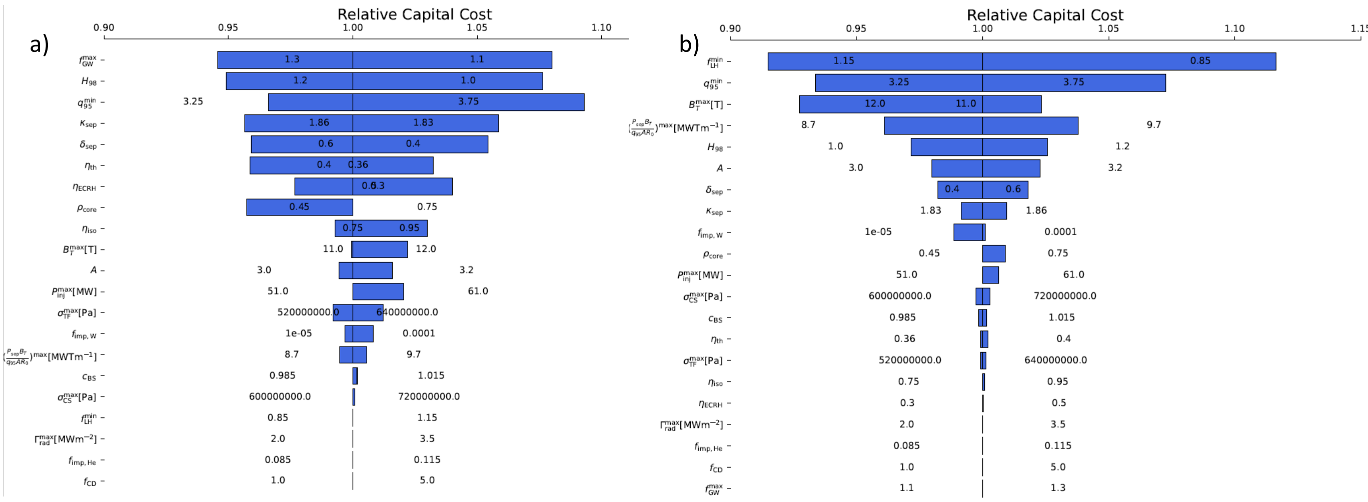

Fig. 1. Panel a) shows a Tornado plot for EU-DEMO 2018 baseline optimising for minimal major radius, whereas Panle b) presents a Tornado plot for EU-DEMO 2018 baseline optimising for maximum fusion gain Q. The numbers placed on the left and right of the vertical bars in these charts denote the optimistic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

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 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 it computationally expensive. Therefore, first we must utilise a parameter screening technique called the method of elementary effects or the Morris method which we will describe in the next section to identify the key parameters to focus our analysis upon.

III. The 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[11]. One key advantage of this method is its relatively inexpensive computationally as compared to variance-based methods. Therefore this techniques is best utilised 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 context of PROCESS in a previous work[12].

We denote the PROCESS model as $y\left(\mathbf{X}\right)$ where $\mathbf{X} = (X_1, X_2, ..., X_k)$ is the i-th model input of set of k inputs considered. The input space is then sampled in a k-dimensional hypercube which has been discretised 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 i-th input factor is given by the expression

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

Where here $\mathbf{e}_i$ is the orthonormal basis vector for the i-th 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 A. Saltelli et al, Global Sensitivity Analysis: The Primer 2008[13]. This procedure produces j elementary effects for each input variable considered, we then study the distributions of these computed values along their trajectories. This is done by identifying sensitivity measures using the two expressions,

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

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

where μ_i^* is the absolute mean of the elementary effects of the i-th parameter and σ_i is the standard deviation of the elementary effects of the i-th model parameter. The absolute mean, shown in Eq. 2, can be seen as providing a ranking of the effect of an input on model output, this allows for easy identification of negligible model inputs. Whereas the standard deviation, shown in Eq 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.

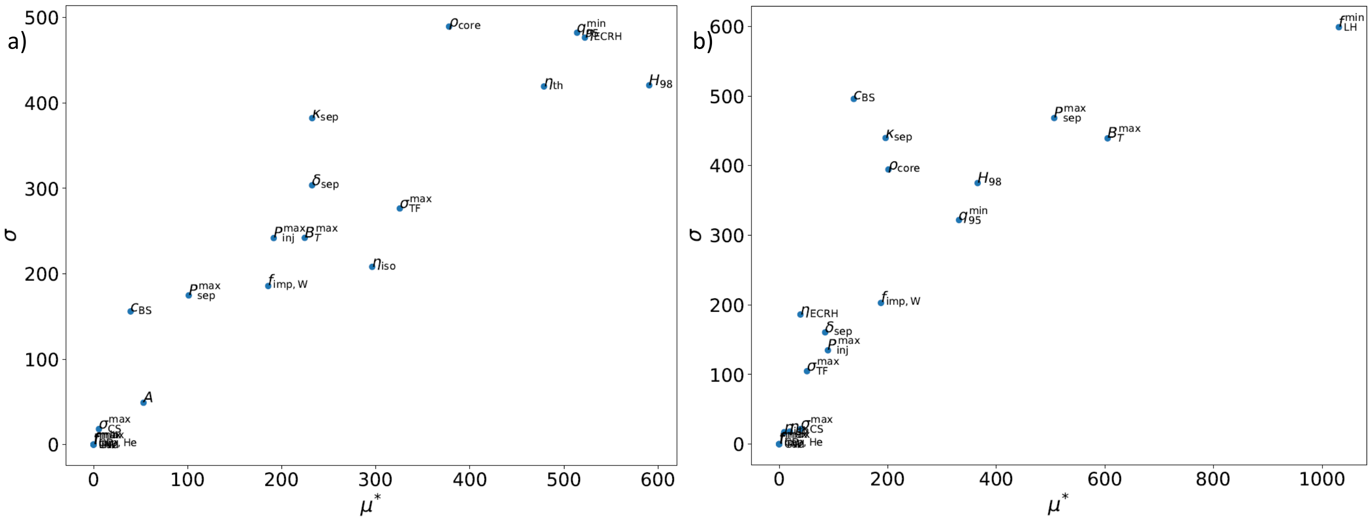

Fig. 2. Panel a) shows A scatter plot showing the absolute mean and variance of the elementary effects of PROCESS physics and engineering parameters for EU-DEMO 2018 baseline optimised by minimising capital cost. While Panel b) shows the scatter plot for the absolute mean and variance of the elementary effects of the same PROCESS parameters for EU-DEMO 2018 baseline optimised for maximum fusion gain Q. Both plots have been created using $r = 25$ trajectories.

All samples will be taken with a flat distribution between their upper and lower limit. 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 8 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 minimising capital cost. We expect parameters which appear in the upper right sector of these plots to be the most consequential model inputs.

Comparing between optimising for a minimal major radius and machine capital cost we see board agreement in the ranking of the effects on the capital cost. The one extreme outline 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 it has $\mu^* = 0$ 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 for a fixed radial build use the fusion gain Q as the figure of merit. If we compare the highest absolute means of the elementary effects to the the single parameter study shown in Fig. 1.b, the same parameters make up the five most influential but apart from the lower bound on the LH threshold being the most important the order of their ranking is different.

IV. The 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 $Var(y|\mathbf{X})$, where the output $y(\mathbf{X})$ variance is obtained 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 $E_{X_{\sim i}}(Var(y|X))$ as compared to the total variance $Var(y)$. The $\mathbf{X}_{\sim i}$ notation here denotes the set of all variables except X_i.

There are 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

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

As the first order only includes the variance from one input parameter it only captures linear behaviour 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 accounts for the total contribution to the model output variation due to the model input X_i, in includes the first order index and all higher order indices arising due to input interactions. They are computed using the expression

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

When sampling the input parameter space we implement the Saltelli sampling. For more information on this sensitivity measure see A. Saltelli et al[13].

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, we also note that their first order Sobol indices are within the 95% confidence interval for the total

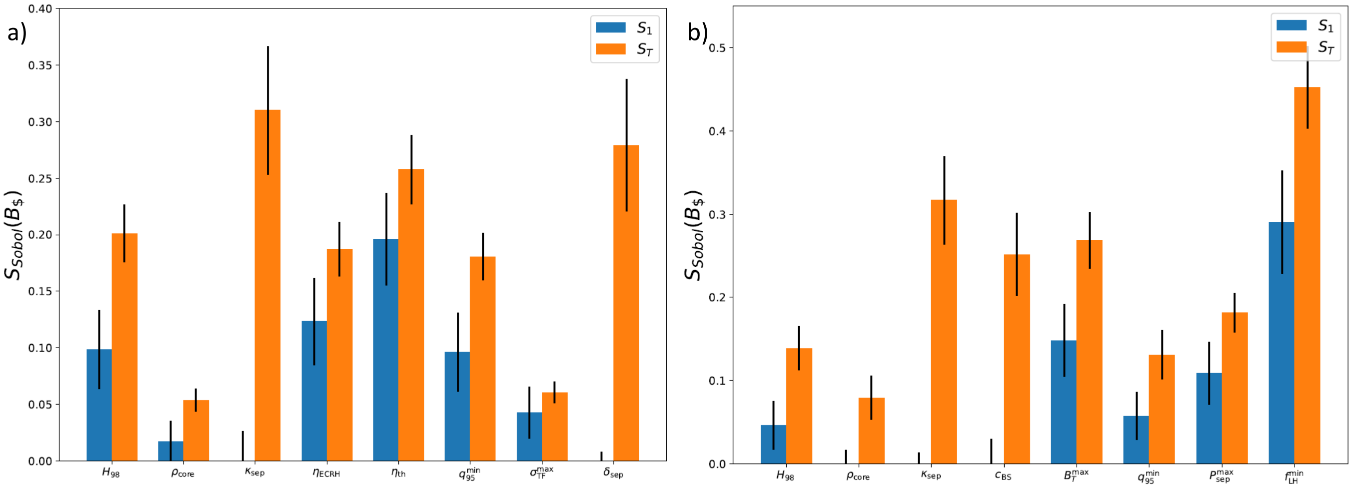

Fig. 3. Here presented are charts showing the first order S_1 and total S_T Sobol indices of screened PROCESS physics and engineering parameters for EU-DEMO 2018 baseline. Panel a) shows Sobol indices for PROCESS when optimised for minimal capital cost. while panel b) presents the Sobol indices for PROCESS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

Sobol indices so we infer that their influence on the machine capital cost in near 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 non-linear and interact with many other model inputs in producing the output capital cost. Indeed, the very high S_T's found for the plasma elongation and triangularity suggest that 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 current have enough PROCESS runs to achieve acceptable statistical certainly in these indices.

Considering now the case of a fixed radial build and optimising 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. That the second largest first order Sobol index is the maximum toroidal field 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 the input parameter space which contains some strongly coupled interactions is caused by the to the high plasma current regime that PROCESS finds solutions within when optimising for fusion gain. The high uncertainties in 95% confidence intervals are due to number of runs used and highlights 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 what to explore for future device we much also consider that for safety reasons the need to operate in regime well above the LH threshold, therefore the pessimistic scenario discussed in section 2 is worth exploring in more detail.

V. Conclusions

This study suggests magnet technologies will be the biggest driver in costs in EU-DEMO and a understanding the uncertainties in various magnet designs 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. And understanding uncertainties in these parameters is crucial for understanding the viability of reactor designs.

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