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Reference Class Forecasting and its application to fusion power plant cost estimates

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***Abstract*— Developments in fusion energy technology and the aspiration to build and run commercial fusion energy power plants has seen the commencement of numerous publicly and privately funded projects in recent years [1,2,3]. Megaprojects, like fusion power plants, by their very nature are inherently complex and risky, therefore providing a robust cost estimate in early stages is challenging. In the fusion sector, this is amplified by the fact that very little data exists on which to base an estimate due to the novel nature of the materials and technologies involved. A common phenomenon during the estimating phase of a new project is the concept of Optimism Bias, where under-estimation of time, cost and risk can cause impacts on the baseline cost and schedule, leading to significant over-runs during the project lifetime. Reference Class Forecasting is a method used to mitigate against these factors, based on using actual performance data in a reference class of comparable projects to improve forecasting accuracy. This article will discuss Reference Class Forecasting, how it has been used in recent megaprojects, and how it is intended to be used in the STEP (Spherical Tokamak for Energy Production) Programme [4] to provide a full programme cost model for a Prototype Fusion Energy Plant.**

***Index Terms*—Cost Estimating, Fusion Power Plant, Optimism Bias, Reference Class Forecasting, Strategic Misrepresentation, STEP**

I. INTRODUCTION

As the nascent fusion energy sector grows, its ambition to build and run commercial fusion power plants to support future energy requirements and to contribute to the net zero targets of governments around the globe, the number of megaprojects associated with fusion technology will increase. As a result, there will be increased scrutiny on the financial aspects of these megaprojects as stakeholders try to understand the commercial viability of a fusion power plant.

Cost estimates will therefore need to increase in accuracy, as we look to deliver value for money and return on investment, whether these be public or privately funded ventures.

Forecasters attempting to provide cost estimates for megaprojects face various challenges, including the complexity of the environment, the presence of uncertainty, and biases, especially at an early stage of concept maturity, where most fusion technologies currently sit.

Optimism Bias and Strategic Misrepresentation are two examples of behavioural biases, which will be discussed in detail later in this article. These biases can lead to unrealistic expectations and poor decision-making, undermining the credibility of estimates and leading to unsatisfactory project performance and outcomes.

Reference Class Forecasting (RCF) is a method that can help forecasters to mitigate biases by comparing the present situation with past situations that are similar [5]. RCF involves identifying a reference class of past cases that are relevant to the current situation and using the statistical properties of the reference class to make predictions about the future. RCF has been shown to be an effective method for improving forecasting accuracy in various domains [6], and this paper will discuss how it is intended to be used on the UKAEA's STEP programme.

II. WHY ARE MEGAPROJECTS DIFFICULT TO ESTIMATE?

Megaprojects, sometimes called "major programmes", are large-scale, complex ventures that typically cost more than 1 billion US Dollars, take many years to build, involve multiple public and private stakeholders, are transformational, and impact millions of people [7]. As such, they are more difficult to estimate for several reasons:

1. Uncertainty

Megaprojects often involve a high degree of uncertainty in terms of their scope, schedule, and costs. This can be due to factors such as unforeseen or novel technical challenges, regulatory requirements and changing market conditions. This is especially true of first-of-a-kind fusion power plant endeavors.

2. Complexity

Megaprojects are often highly complex, with many different components and subsystems that must be integrated and coordinated. Complexity is not limited to technical aspects, but also includes people and interfaces. This makes it difficult to accurately estimate the time and resources required. Fusion power plants are highly integrated technologies, where changes in one area often impact multiple others in non-linear fashion.

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3. Dependencies

Megaprojects typically involve many interfaces and stakeholders, including suppliers, contractors, and regulatory agencies. These stakeholders are predominant and can have a significant impact on the project timeline and costs, and their actions may be difficult to predict. Fusion power plants are typically multi-party programmes that bring together multiple stakeholders from governments, regulators, over private investors to multiple manufacturers and construction companies.

4. Scale

Megaprojects are often much larger in scale than other types of projects, which can make it difficult to accurately estimate the resources required. Megaprojects cannot just be assumed to be linear in terms of scaling up or down from a starting point, it can be much more complex in practice. For example, the construction of a large infrastructure project may require thousands of workers and millions of pieces of equipment, requires excellent project management processes and skills to manage and coordinate. While many private fusion companies aim for small plant sizes from micro-reactors of 5kWe to small reactors of up to several hundred MWe [1], publicly funded programmes typically assume only larger systems can be commercially relevant. Nevertheless, even ~100MW fusion power plants can still be expected to have sufficiently large scale to be considered a Megaproject.

In summary, the sheer size and complexity of megaprojects make them much more difficult to estimate correctly. The effect of multiple stakeholders and interfaces combine to create feedback that is unpredictable. Therefore, an estimating methodology such as Reference Class Forecasting can be effective to help mitigate the risks in providing estimates for such large-scale projects of which fusion power plants are one example.

III. POOR PERFORMANCE IN MEGAPROJECTS

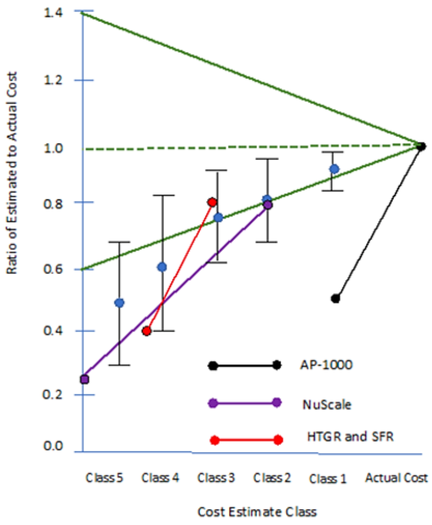

Fig. 1. Cost estimation in large complex projects showing that as designs mature and incorporate more detail, cost uncertainty decreases but (more importantly) actual cost increases significantly [8]. The examples show data from fission power plants using AACE estimating classes [9].

The challenge of providing cost estimates for megaprojects, especially in the early stages, is discussed in detail in [8]: “Early-stage cost estimates are unreliable predictors of the eventual cost of megaprojects. This is valid across all nuclear technologies and also large non-nuclear megaprojects.”

Based on research performed for STEP, using publicly available data, common trends emerge that drive cost increases:

1. Increase in material and labour costs

2. Underestimating complex engineering requirements associated with project.

3. Over optimistic bias with regard to the initial estimate.

4. Initial estimate not based on eventual project scope.

5. Design changes throughout construction incurring additional design costs and incurring additional costs due to timeframe extension.

These 5 trends align well with the “Causes of Poor Performance” diagram produced by the Associated for Project Management (APM) [10]

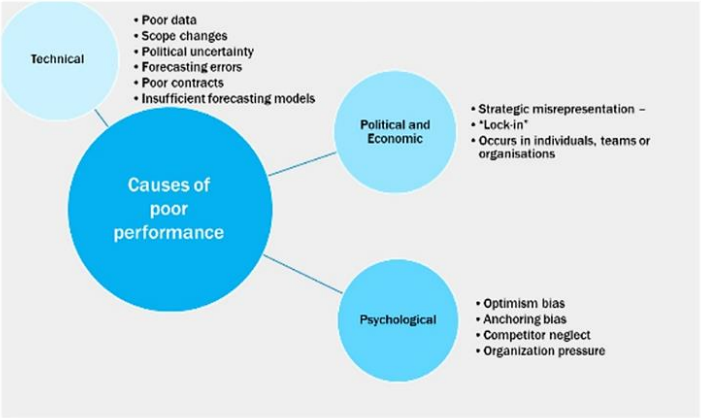

Fig. 2. Causes of Poor Performance; Technical, Political and Economic, Psychological [10]

Flyvberg describes in [11] the typical attributes of underperformance as “numerous uncertainties such as project complexity, technological uncertainty, demand uncertainty, lack of scope clarity, unexpected geological features, and negative plurality (i.e., opposing stakeholder voices).”

The conclusion of Flyvbergs’s work being that while all of these factors contribute to cost overruns, benefit shortfalls, and time delays; it is not important to explain how to overcome these. Rather to explain why costs, benefits, and time forecasts for more complex projects are systematically over-optimistic in the planning phase in comparison to less-complex projects. In other words, “why do project planners, on average, fail to anticipate the greater costs of complex projects or those based on new technologies?”

IV. RCF METHODOLOGY

RCF is a method of forecasting that involves identifying a reference class of similar events and analysing their historical data to predict the likelihood of future outcomes. The reference class is a set of past events that are similar in relevant respects to the event being predicted. For example, if we want to predict the outcome of an engineering project, we will look at the historical data of similar engineering projects in terms of scope, budget, and timeline; and use this data as a comparison for our new project.

RCF was first introduced by Daniel Kahneman and Amos Tversky in their 1979 paper [5]. The authors defined reference class forecasting as "the use of similarity-based reasoning to predict an unknown quantity or outcome."

Kahneman and Tversky found human judgment to be generally optimistic due to overconfidence and insufficient regard to distributional information. Thus, people will underestimate the costs, completion times, and risks of planned actions, whereas they will overestimate the benefits of the same actions. Lovallo and Kahneman [12] call such common behaviour the “planning fallacy” and argue that it stems from actors taking an “inside view,” focusing on the constituents of the specific planned action rather than on the outcomes of similar already completed actions.

The RCF approach mitigates optimism bias and strategic misrepresentation by taking the “outside view”. It uses a database of actual performance of comparable past projects within a given reference class to provide an objective reference point for the cost forecast of a current project [13].

Optimism bias is a cognitive bias that causes people to overestimate the likelihood of positive events and underestimate the likelihood of negative events (or *‘delusion’*). This bias can have significant implications for decision-making, as it can lead individuals to make overly optimistic or unrealistic predictions about the future.

On the other hand, strategic misrepresentation (or political bias) is a deliberate and intentional act of providing false or misleading information in order to gain an advantage in a particular situation (or ‘*deceit’*). The motive behind strategic misrepresentation is to maximise one's own benefits and minimize the risks.

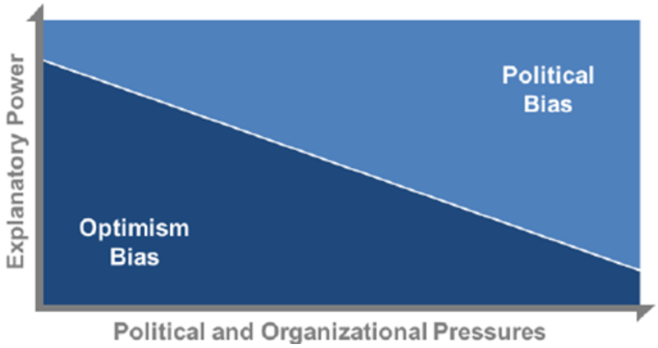

Fig. 3. Explanations of Risk in Projects; Optimism Bias and Strategic Misrepresentation (Political Bias) [14]

In practice, there is no “standard” RCF code of practice. Variations exist on how the approach is applied.

The main challenge for applying the RCF method is the accumulation of a sample of similar projects with large enough sample size and accurate cost information. It may take a very long time to develop such a database [15]. Using the example of a Fusion Power Plant, it may never be possible to have a sample size large enough for statistical analysis. The problem is further exacerbated by the fact that private companies may not be willing to share such commercially sensitive information with competitors or the governmental agencies.

More specifically, reference class forecasting for a particular project requires the following steps [11]:

A. Select a reference class

Identification of a relevant reference class of past, similar projects. The class must be broad enough to be statistically meaningful but narrow enough to be truly comparable with the project at hand.

B. Assess the distribution of outcomes

Establishing a probability distribution for the selected reference class. This requires access to credible, empirical data for a sufficient number of projects within the reference class to make statistically meaningful conclusions.

C. Make an intuitive prediction of your project’s position in the distribution

Predicting where the specific project lies within the reference class distribution, to establish the most likely outcome for the specific project. Because this intuitive estimate is likely to be biased by the decision maker, the final two steps are intended to adjust the estimate to improve accuracy

D. Assess the reliability of your prediction

The intention of this step is to gauge the reliability of the forecast made above, by estimating the correlation between the forecast and the actual outcome, expressed at a coefficient between 0 and 1. This can be based on available data, for example how well past predictions have matched the actual outcome, or more subjective estimates of predictability.

E. Correct the intuitive estimates

Due to biases, the intuitive estimate will likely be optimistic. This final step adjusts the estimate toward the average based on the analysis of predictability above; the less reliable the prediction, the more the estimate needs to be regressed towards the mean.

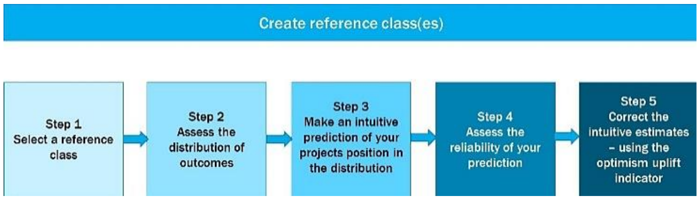

Fig. 4. Implementation of reference class forecasting in 5 steps [10,11]

Figure 5 shows what reference class forecasting does in statisticians’ language. First, reference class forecasting regresses the best guess of the conventional forecast—here the project promoters' forecast, indicated by the dashed curve—toward the average of the reference class. The distribution of outcomes in the reference class is indicated by the dotted curve. Second, reference class forecasting expands the estimate of interval in the conventional forecast to the interval of the reference class [16].

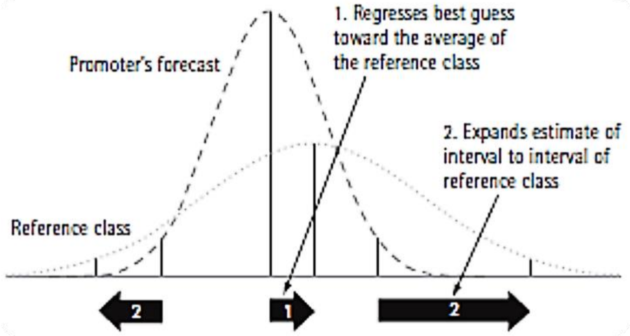

Fig. 5. What reference class forecasting does, in statisticians' language [16]

Overall, reference class forecasting is a powerful tool that can help project teams to estimate the likelihood of success or failure for a current project. By looking at similar projects in the past, project teams can make more informed decisions about budget, timeline, and risk management.

Reference class forecasting can lead to more accurate predictions and decisions, but it can also lead to overconfidence if the past data and experience do not accurately reflect the current situation. Similarly, optimism bias can lead to positive outcomes, such as motivation and confidence, but it can also lead to unrealistic expectations and poor decision-making.

V. EXAMPLES OF RCF IN PRACTICE

Whereas Kahneman and Tversky developed the theories of reference class forecasting [5], Flyvbjerg and COWI developed the method for its practical use in policy and planning, which was published as an official Guidance Document [17]. Below we summarise a few examples of reference class forecasting in large infrastructure projects that have some commonality with fusion power plant programmes in terms of size, complexity and impact.

The first instance of reference class forecasting in practice is described in [18]. This forecast was part of a review of the Edinburgh Tram Line 2 business case, which was carried out in October 2004 by Ove Arup and Partners Scotland. At the time, the project was forecast to cost a total of £320 million, of which £64 million (25%) was allocated for contingency. Using the newly implemented reference class forecasting guidelines, they calculated the 80th percentile value for total capital costs to be £400 million (57% contingency). Similarly, they calculated the 50th percentile value to be £357 million, (40% contingency). The review further acknowledged that the reference class forecasts were likely to be too low because the guidelines recommended that the uplifts should be applied at the time of decision to build, which the project had not yet reached, and that the risks therefore would be substantially higher at this early business case stage. On this basis, the review concluded that the forecasted costs could have been underestimated. The Edinburgh Tram Line 2 opened three years late in May 2014 with a final outturn cost of £776 million, which equals £628 million in 2004-prices [14].

Following the Edinburgh Tram project, reference class forecasting has been used by the UK government's Infrastructure and Projects Authority (IPA) as part of its project assurance process.

By using reference class forecasting, the UK government aims to improve the accuracy of project cost and time estimates, reduce the risk of cost overruns and delays, and ensure that taxpayers' money is used effectively. This approach has been used in several high-profile projects, including the Crossrail railway project in London and the High Speed 2 (HS2) rail service programme.

Crossrail

Crossrail is a large, complex programme to run new, direct rail services between Reading and Heathrow Airport at the western ends of the railway, to Shenfield in Essex and Abbey Wood in south-east London at the eastern ends. When complete, the railway will be around 73 miles (118 kilometres long), stopping at more than 40 stations, including 10 new stations and 26 miles (42 kilometres) of new tunnels [19].

The initial cost estimate released in 2010 was £14.8bn. Due to multiple delays and cost increases, this was revised in 2019 to £17.6bn. A final estimate was given in 2021 of £18.9bn. This equates to a circa £4.1bn overrun, or a cost increase of 128%. In terms of schedule, the initial opening date of December 2018 has slipped to 2023 for full services [20].

"Early in its development, Crossrail was innovative in its rejection of optimism bias in favour of Quantitative Risk Assessment (QRA) techniques. This resulted in Crossrail's reporting of Anticipated Final Crossrail Direct Cost (AFCDC) at P50 and P95." [21] Considering the outcome of the project, it can be argued that this rejecting a RCF approach for a more traditional QRA assessment may have contributed to the cost & schedule over-runs.

Causes for cost and schedule increases are described in [20] however it is clear that cognitive biases were inherent in the project, especially during the 2015-2019 period when the project began to slip.

Post 2019, a new management team was appointed and various measures put in place, including RCF assessments and financial incentives. However these ultimately had limited success due to the new management team uncovering various unknown problems and additional work [20].

High Speed 2 (HS2)

High Speed 2 is the ambitious programme to create a new high-speed rail service from London to Manchester and Leeds, via Birmingham and the East Midlands. The programme is split into 3 phases; Phase 1 between London Euston and the West Midland due 2026; Phase 2a between the West Midlands and Crewe due 2027; Phase 2b completing the full network to Manchester and Leeds due 2033.

From the initial 2011 Economic Case the cost estimate for HS2 has spiralled from £48bn to £125bn for the 2020 Full Business Case, a cost over-run of 260% [22].

RCF was used to set the £40bn target cost and £45 funding envelope for Phase 1 [23]. The RCF was carried out by

Oxford Global Projects, using a dataset of 526 projects. The Department complemented the RCF analysis with HS2 Ltd's quantitative cost risk assessment. The £45bn funding envelope is based on RCF at the P75 delivery confidence, which added approximately 37 per cent to costs to go. This equates to £10bn of contingency and would provide for sufficient funding for potential cost overruns in 75 per cent of the reference class sample. The £40bn target cost is calculated by taking the Phase One point estimate (£34.7bn) and adding contingency based on a P50 delivery confidence from the reference class forecast, an 18 per cent adjustment on the costs to go, approximately £5bn [24,25].

Optimism Bias (OB) has been set at 40% for HS2 Phase 2 [26], which would seem to be low in relative terms if compared to other infrastructure projects in the same reference class. Future RCF for Phase 2 will clarify whether this assumption proved to be correct; however recommendations in [22] suggest over-optimistic cost estimates and optimism bias are still an inherent problem.

AACE International (the Association for the Advancement of Cost Engineering) include Estimate Validation as a distinct step in the recommended practice of Cost Estimating "The estimate should be benchmarked or validated against or compared to historical experience and/or past estimates of the enterprise and of competitive enterprises to check its appropriateness, competitiveness, and to identify improvement opportunities. Validation examines the estimate from a different perspective and using different metrics than are used in estimate preparation." [27]

In the process industries, which tend to dominate AACE's membership, benchmarking of project cost estimates against the historical costs of completed projects of similar types, including probabilistic information, has a long history [28].

While estimate validation is similar to RCF in that it calls for separate empirical-based evaluations to benchmark the base estimate, it must be noted that it cannot be directly compared to RCF, as benchmarking can take place using smaller / narrower data sets. However the concept of data validation being performed in practical applications based on empirical data is relevant and demonstrates that such a technique, i.e. RCF, can be applied in the fusion sector.

VI. USE ON STEP PROJECT

STEP (Spherical Tokamak for Energy Production) is a UK Atomic Energy Authority (UKAEA) programme that will demonstrate the ability to generate net electricity from fusion [4]. It uses RCF as part of its best practice approach to costing fusion power plants.

In 2023, STEP became part of the UK Government Major Projects Portfolio (GMPP). GMPP comprises the largest, most innovative, and highest risk projects and programmes delivered by the UK government. Projects on the GMPP receive independent review and assurance from the Infrastructure and Projects Authority (IPA). As part of the IPA's Principles for Project Success, RCF is a requirement of all GMPP projects as part of its assurance processes and is mandated in The Green Book guidance issued by HM Treasury.

The STEP programme has commissioned work to determine relevant reference classes that can be applied to their cost estimating models. A reference class of more than 250 global projects worth over $600 billion was collected across numerous project types and sectors.

The result of this work is confidential and cannot be shared, however gave the STEP programme an initial P50 Cost Overrun and Time Overrun percentage that can be used to adjust future cost estimates.

Further work was performed using publicly available data as a validation exercise. Initial research was undertaken to discover programmes that match the defined criteria, i.e. similar scale, complexity and novelty. Exact matches are difficult to locate, each programme used for comparison must be considered in accordance with their own conditions of development and execution when being used to apply an adjustment to the STEP programme estimate.

The following chart (Figure 5) and table (Table 1) contain data from a collection of case studies to provide support to UKAEA in terms of reference class forecasting. It compares the Initial Estimate, Outturn Cost and % uplift from initial project estimate.

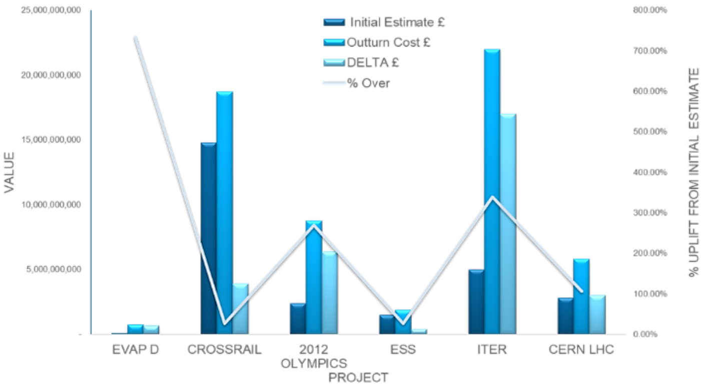

Fig. 5. Comparison of financial performance of selected projects in monetary value and percentage uplift

TABLE I

COST OVERRUNS IN COMPARABLE PROJECTS

Description	Initial Estimate	Outturn Cost	% Uplift to Initial Estimate	Avg % Uplift
6 Identified Projects	26.5b	57.9b	118%	250%
STEP Specific Projects	9.3b	29.6b	220%	158%
General Infrastructure	17b	27.5b	60%	148%
Identified Possible Worst Case Example	90m	750m	733%	
Total				**185%**

As can be seen from the results of the data produced, a percentage uplift from initial estimate of 118% across the reference class was identified.

This data is based on a very small subset and should not be considered a large enough range to be suitable for a standard reference class; guidance suggests a sample size of 20 to 30 projects minimum. However, it suggests that typical fusion power plant projects might consider applying an uplift in excess of 100% to their initial cost estimates, possibly even higher in the early stages of design.

Further lessons learned from fusion specific cost estimates come from the NSCX programme [29] that was cancelled due to significant cost over runs in relation to externally validated, early estimates (post-concept design, but pre-prototype manufacturing trials) due to its FOAK nature and a massive underestimation about the amount of rework required in manufacturing to meet the high quality requirements of the design. Suggesting that other fusion FOAK endeavors can easily suffer similar types of optimism bias.

VII. CONCLUSION

Reference Class Forecasting and its potential to mitigate biases can have a significant impact on the accuracy of cost estimates. While RCF can help to reduce uncertainty and risk by providing decision-makers with empirical evidence based on past experiences, behavioural biases such as Optimism Bias and Strategic Misrepresentation can lead to overconfidence and unrealistic expectations. Therefore, it is essential for estimators and decision-makers to be aware of both concepts and to use RCF as a tool to counteract bias inherent in the estimating process. By doing so, they can make more informed decisions that are based on evidence and avoid these pitfalls.

Reference Class Forecasting can be a powerful tool in the armory of cost estimators to help avoid underestimation of costs in total programme cost forecasts, especially in the early stages of megaprojects.

However, RCF is not without its limitations. Practitioners should be aware of these limitations and take steps to ensure that their predictions are as accurate as possible by benchmarking or validating their results.

In the UK, RCF has been used in an increasing number of cases for publicly funded projects overseen by the IPA. Experience gained in these applications should be collated and should be used to help the production of cost estimates for the STEP project. By continuing to liaise with industry and government, STEP can drive best practice and build and maintain the most representative reference class available.

At present, use of Reference Class Forecasting in Fusion applications cannot be based on direct comparisons with other Fusion projects, as no direct data sets are available. Therefore, it is essential that the reference classes selected for Fusion applications are suitable and validated until such a time exists that directly relevant fusion data sets exist. Clearly this will require a collaborative approach from all interested parties, and co-operation between private and publicly funded organisations.

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