Nuclear Engineering and Design 328 (2018) 145–153

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

The application of portfolio selection to fuel channel inspection in advanced gas-cooled reactors

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ARTICLE INFO

Keywords:
Advanced gas cooled reactors
Fuel channel inspection
Genetic algorithms
Portfolio analysis

ABSTRACT

The continued operation of the UK's advanced gas-cooled nuclear reactors is dependent upon inspections of the graphite core to provide information on the evolution of core properties (such as the shapes of individual graphite bricks). It is necessary to optimise the information that is obtained, and the question of which fuel channels to inspect is a portfolio selection problem, complicated by the fact that the solution space is large and cannot be searched exhaustively. In addition, a number of portfolio–specific selection criteria must be applied, including the need to inspect channels in an even distribution across the core. A genetic algorithm is used to find a near-optimal solution, adapted so that portfolios potentially able to breed better offspring in future generations are accounted for. Analysis of the portfolios is an important part of the channel selection problem and algorithms have been developed to determine the significance of individual elements within the portfolio and the sensitivity of utility to portfolio size. The methods developed have been implemented in the CHANSELA software, the use of which contributes to the demonstration of the continued safe operation of the reactors.

1. Introduction

The UK currently has 14 advanced gas-cooled reactors (AGRs) operated by EDF Energy, making a major contribution to the country's total electricity supply. The cores of reactors have thousands of interlocking graphite bricks which, when viewed from above, resemble a honeycomb of circular channels, as shown in Fig. 1. It is within these channels that the fuel rods are lowered to initiate the nuclear reaction.

The continued safe operation of the reactors is underpinned by an extensive programme of testing and analysis, including the use of data gathered from the reactor during periodic shutdowns. The inspection of the channels within the graphite core, by remote TV cameras, sample removal and other techniques during these routine shutdowns provides information on the status of the core.

The amount of information that can obtained at an inspection must be balanced against economic and other considerations. It is not practical to inspect every channel in the reactor, but sufficient information on the state of the core can be obtained by inspecting far fewer channels. An AGR contains approximately 300 fuel channels and typically around 30 are inspected at each shutdown.

Bricks in the reactors have different characteristics: some may be more or less prone to weight loss or cracking because of factors such as their position in the reactor, or the batch of virgin graphite from which they were produced; some channels may have a long history of repeat inspections whilst other channels may never have been inspected. Inspecting different selections of these channels will therefore provide different types and amounts of information on the status of the graphite core. The problem faced, therefore, is which channels, out of the 300 or so that are available to inspect, are likely to provide the optimum information at a given inspection.

2. Theory

2.1. Overall approach

The problem described in the Introduction is an example of a multi-criteria portfolio decision analysis (MCPDA) problem. Portfolio selection is a challenge faced by decision makers in numerous fields, for example: selecting the best portfolio for financial investment (e.g. Markowitz, 1952; Steuer et al., 2008); creating a menu (e.g. Chien & Sainfort, 1998); military and defence planning (e.g. Burk & Parnell, 2011; Kangaspunta et al., 2012); selecting projects for research and development (e.g. Henriksen & Traynor, 1999; Bitman and Sharif, 2008); and planning land use (e.g. Stewart et al., 2004).

There are many approaches that have been employed to tackle such problems. The simplest is the scoring model, where elements (a generic term for the items to be chosen) are scored on each of the criteria for selection and the scores are then weighted and combined to give an

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https://doi.org/10.1016/j.nucengdes.2018.01.013
Received 28 August 2017; Received in revised form 1 January 2018; Accepted 3 January 2018

Fig. 1. The lattice of graphite bricks comprising the core in an advanced gas-cooled reactor.

overall metric (e.g. Henriksen and Traynor, 1999; Cooper et al., 2001). Multi-Attribute Utility Theory (MAUT) is a scoring model that makes use of a utility function, which may be additive or multiplicative, that is maximised to find the optimum (e.g. Dyer et al., 1998). Saaty (1980) developed the Analytic Hierarchy Process (AHP), which involves comparing elements in pairs (e.g. Thurston & Tian, 1993). Analytic Network Process (ANP) (Meade and Sarkis, 1999) is a generalised form of AHP allowing for more complex interrelationships among elements and selection criteria (e.g. Meade & Presley, 2002). Goal programming introduces flexibility in the criteria, where the goals do not have to be met but penalties are applied for missing goals, giving another criterion to minimise (e.g. Stewart et al., 2004).

In cases where there are a large number of possible portfolios to evaluate, heuristic techniques may be applied to search for near-optimal solutions. Examples include ant colony optimisation algorithms (e.g. Doerner et al., 2004), simulated annealing (e.g. Crama & Schyns, 2003) and genetic algorithms (e.g. Arnone et al., 1993, Stewart et al., 2004; Lin & Liu, 2008).

The channel selection problem considered here has the following characteristics:

1. The search domain is large, and the identification of a single near-optimum solution is generally satisfactory. There is no requirement to generate or assess all viable portfolios.
2. All information relevant to portfolio selection is deterministic.
3. The portfolio selection involves both element-specific and portfolio-specific ("balance") criteria.
4. Analysis of portfolio properties is a key part of the process, particularly as the final number of elements selected may be different from the original intention.

The first of these characteristics indicates that heuristic approaches are appropriate; indeed such a large search domain precludes the use of other techniques. In many cases there will be several portfolios that are near optimal, and there may not be a single well-defined optimal solution. A scoring or utility approach that can be automated is needed, rather than techniques that require manual input. As indicated by the second characteristic, no risk or uncertainty is involved, so this is not a problem of the type that is commonly found in the financial sector as described by Markowitz (1952). The third characteristic means that single-element multi-criteria decision analysis (MCDA) is not appropriate in this situation and a portfolio selection approach is what is required.

The importance of the fourth characteristic derives, for example, from the fact that operational constraints that were not anticipated before an inspection may mean that it is not possible to inspect all channels originally planned; it is then necessary to decide which channel(s) is least important and can be omitted from the inspection. It may also be useful to know how much more information would be obtained if more channels were inspected; it may be the case that the amount of information obtained will not increase significantly after a critical number of channels has been inspected. In addition, comparison of the properties of the selected portfolio with 'handpicked' portfolios may be helpful in identifying key features of the problem.

With the above characteristics in mind, a utility function approach is employed to rate individual portfolios. Rather than scoring every possible portfolio (of which there are typically 300!/30! × 270!), which evaluates to approximately 10^{41}), a genetic algorithm (e.g. Haupt & Haupt, 2004) is used to generate a much smaller number of potential portfolios and breed from the most highly rated to create subsequent generations and ultimately arrive at an optimal or near-optimal solution.

The details of the methods employed are discussed below in general terms, with further details of the channel selection application given later in the paper and in the Appendix.

2.2. The utility function

Assuming that the criteria for selection are independent from each other, then the standard additive utility model described by Keeney and Raiffa (1993) can be applied (otherwise a multiplicative form should be used, also discussed in Keeney & Raiffa, 1993). If a total of N elements are to be selected, with each element evaluated against a total of M criteria for selection, then the utility function, u, can be written as

$$u = p\sum_{i=1}^{M} w_i u_i$$

where w_i is a weighting for criterion i and u_i is a single-attribute utility function over criterion i that ranges from 0 to 1. The form of the function used will depend on the criterion in question, but all will be a function of the number of elements included in the portfolio that have the specific attribute linked to the criteria. The best outcome results in a single-attribute utility function value of 1, whilst the worst gives a value of 0.

The weighting factors w_i are interpreted in this context as the "importance" of each criterion, and need to be specified as inputs. These weights are defined as relative values such that

$$\sum_{i=1}^{M} w_i = 1.$$

In the channel selection problem the Analytical Hierarchy Process (AHP) is generally used to define the weighting factors. This method is described by Saaty (1980). In this approach the different criteria are compared in pairs, with a numerical value being assigned to indicate which criterion is more important. A five-point scale is generally employed, such that:

- Information type A much more important than B: Score 5
- Information type A more important than B: Score 3
- Information types A and B are equally important: Score 1
- Information type A less important than B: Score 1/3
- Information type A much less important than B: Score 1/5

A matrix is used to record the scores, and this enables the weights to be employed to be calculated.

The penalty factor, p, modifying the utility function from the standard form used elsewhere, represents portfolio-specific or balance criteria. Such criteria act on the portfolio as a whole and are used to