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An exploration of the relationship between nuclear decommissioning projects characteristics and cost performance

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ABSTRACT

Nuclear Decommissioning Projects and Programmes (NDPs) are characterized by high complexity and variety, and a schedule that can take decades. Moreover, NDPs estimates at completion can reach billions of Euro and (for many of these projects) keep increasing, while there is a limited understanding of why this happens. To address this knowledge gap, this paper describes how to statistically test the association between the NDP characteristics and the NDP cost performance. The implementation of statistics on a pool of European NDPs highlights the significance of several country-specific and site-specific characteristics (e.g. respectively, the governance system and the availability of facilities to deal with radioactive material on site). Hence, the original contribution of this paper consists in (i) the selection of statistical tests suitable for analysing small sample sizes (i.e. NDPs) and (ii) the presentation of the results from the implementation of these tests on a pool of 24 European NDPs with an illustrative purpose.

1. Introduction

Until now, the nuclear sector and its stakeholders (industry, academia, policy-makers etc.) have mostly focused on the design and construction of new nuclear infrastructure while, in comparison, the body of knowledge on decommissioning is more limited. Indeed, more than 500 Nuclear Power Plants (NPPs) have been built in the world, but only 16 NPPs have been fully decommissioned (OECD/NEA, 2016). However, due to safety, security, economic, environmental, social and ethical reasons, in the near future, more and more nuclear facilities will need to be decommissioned, and a number of new challenges will arise.

Decommissioning encompasses all the "*administrative and technical actions taken to allow the removal of some or all the regulatory controls from a facility, except a repository which is closed and not decommissioned*" (IAEA, 2017). Nuclear Decommissioning Projects and Programmes (NDPs) are therefore here intended as site-level projects and programmes undertaken to restore the site to new use.

NDPs are characterized by extremely diverse inventories of radiological material, whose handling increases the project complexity and uncertainties. NDPs range from smaller projects like the decommissioning of Vandellós-1 NDP (in Spain), whose final costs of the work to reach dormancy in 2003 was €94.6million (IAEA, 2011, p.55), to major national multibillion projects, like Sellafield NDP (in the UK). Indeed, Sellafield alone reaches almost £120bn (€136bn), i.e. more than 70% of the decommissioning cost estimates of the whole UK nuclear legacy, which is estimated at £163bn (€185bn) (NDA, 2017b). Additionally, year after year, the estimates at completion for some of these NDPs keep increasing (see Table 2 in section 2.2), and there is only a limited understanding of why this happens. Consequently, there is a need to systematically investigate which are the NDP characteristics that mostly impact on the NDP cost performance.

NDP characteristics encompass country-specific characteristics (such as the governance, the funding and the regulatory environment, etc.), site-specific characteristics (such as the age and the operational history of the nuclear facility, etc.) and management-related characteristics (such as scope definition and planning of the NDPs). For illustrative reasons, the NDP performance are assessed in this paper in terms of the NDP cost performance, however this approach can be applied to other project performance (such as time, safety, etc.). The NDP characteristics and the NDP performance are described in more detail in section 2.

Until now, only limited research has investigated NDPs from the project management perspective, and the literature still lacks a systematic analysis to assess the association between NDP characteristics and NDP performance.[1] Therefore, this paper describes a methodology based on benchmarking to analyse NDPs, focusing on the selection and

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[1] If statistical analysis is applied to test the "relationship" between categorical variables, the term "association" is used.

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Table 1
Example of a 2 × 2 contingency table.

Contingency Table		NDP Performance (i.e. is the project within 10% cost overruns?	
		Yes	No
NDP Characteristic (e.g. is the NDP in the UK?)	Yes	a	c
	No	b	d

application of suitable statistical tests to address this knowledge gap.

Indeed, benchmarking is ideal to compare actual or planned practices in order to identify best practices and generate ideas for improvement (PMBOK, 2013), as it is a flexible approach that can address the alleged uniqueness of NDPs. Indeed, every project can be argued to be "unique" (PMBOK, 2013). NDPs can be seen as "more unique" than other projects due to their complexity and variety of their design, the legal requirements to decommission them, the stakeholders involved, etc. However, lessons from benchmarking NDPs can still be learned, but benchmarking needs to firstly be adapted to the context of NDPs (Invernizzi et al., 2018a).

Indeed, in parallel with the growth of the decommissioning industry, the information available on decommissioning will also increase in the next decades. This information will be both qualitative and quantitative in nature, so there is a need to develop a robust methodology to guarantee a systematic analysis, in which both qualitative and quantitative data are used, and that lessons can be learned and re-applied to seemingly unique projects.

This aim of this paper is to present a systematic approach to test the association between the NDP characteristics and the NDP performance through statistics. Therefore, two statistical tests that are suitable for investigating NDPs (which consists of a small sample size) are selected and applied on 24 European NDPs with an illustrative purpose.

The remaining part of the paper proceeds as follows: section 2 reports the methodology based on benchmarking developed to investigate NDPs, detailing the process of selection of the statistical tests suitable for small sample sizes. Then, these statistical tests are applied on European NDPs; results are presented in section 3 and discussed in section 4; section 5 highlights the limitations of this analysis, while section 6 concludes the paper, paving the way for future research.

2. Adapting benchmarking to nuclear decommissioning

Invernizzi et al. (2018a; 2017a) presented a selection of benchmarking studies both in the nuclear and non-nuclear sector, highlighting that the meaning of the term "benchmarking" has been widely discussed in the last decades, and that a number of different benchmarking processes are presented in the literature (e.g. see (Anand and Kodali, 2008)). Invernizzi et al. (2018a; 2017a) also proposed a methodology based on benchmarking and tailored for NDPs, based on 5 steps:

1. Research initiation, which refers to the gathering of information to understand the context in which the NDP progress;
2. Data collection, which is a systematic recording of information on the NDPs;
3. Operationalization of the NDP characteristics and the NDP performance (i.e. respectively the independent and dependent variables of this analysis). This consists of creation of a systematic list of the NDP characteristics that impact on the NDP performance, and their codification into non-arbitrary constructs;
4. Implementation, which refers to the actual "problem solving", and it is split into two stages:
   4.1. Cross-comparison of NDPs
   4.2. Statistical analysis implemented on NDPs
5. Validation and dissemination, which provides confirmation of the findings and enables sharing both the methodological and practical learnings, which will be further developed in future work.

Step 4.2, i.e. the statistical analysis, is a fundamental part of this research, as it highlights the potential association between the NDP characteristics and the NDP performance. This paper focuses on step 4.2. The choice and implementation of the statistical analysis is grounded on previous research (Locatelli et al., 2017b; Locatelli et al., 2017c; Brookes and Locatelli, 2015), which this paper develops both in terms of the selection of the statistical tests and their application on NDPs.

The five steps of the methodology based on benchmarking and described above, the selection of the Barnard's test alongside the Fisher's exact test, and their implementation on NDPs are described in detail in the next sections.

2.1. Research initiation

The research initiation is the first step to benchmark NDPs, and includes a scrutiny of the information available on NDPs, early scoping interviews with experts and site visits (section 2.1.1), as well as the selection of suitable statistical tests to be implemented (section 2.1.2). This lays the foundation for a sound understanding of the context in which NDPs progress, sets the boundaries of the research and enables a systematic collection of information.

2.1.1. Exploration of the literature and collection of primary data

The exploration of the literature showed the limited attention posed by academics on the infrastructure end-of-life and management of NDPs. Conversely, publications by international organizations, such as the International Atomic Energy Agency (IAEA/OCED-NEA, 2017; IAEA, 2011), the OECD/Nuclear Energy Agency (OECD/NEA, 2016; OECD/NEA, 2015; OECD/NEA, 2012) and the European Commission (EU, 2015) on this topic have recently flourished. These publications are some of the most relevant sources of information used to understand the NDPs context and collect the NDP characteristics that are recognized to have an impact on the NDP performance. Relevant publications reviewed for this research also include:

- The European Court of Auditors reports (2016; 2011), which discuss the progress of the decommissioning in Lithuania, Bulgaria and Slovakia, stressing (among others NDP characteristics) the consequences of not having a storage facility available;
- the Öko-Institut report (2013), which compares French NDPs by EDF, the Sellafield/NDA case and Greisfwald NDP in Germany;
- The reports by the UK National Audit Office (NAO, 2018; NAO, 2015; NAO, 2012), which describe major projects in Sellafield and the technical and organizational issues that they are facing, as well as contractual challenges concerning the governance of the Magnox NDPs (NAO, 2017).
- Laraia's book (2012), which describes several aspects of nuclear decommissioning, ranging from technical to managerial ones, even providing a list of empirical cases;
- The paper by Torp and Klakegg (2016), that explains the challenges in cost estimation under uncertainty in the context of nuclear decommissioning;
- The paper by Invernizzi et al. (2017), where a cross-comparison between two NDPs, i.e. Rocky Flats (US) and Sellafield (UK) was performed;

These publications allowed to build a preliminary list of NDP characteristics that impact on the NDP performance. Nevertheless, none of these publications statistically tests the association between the NDP characteristics and the NDP performance.

To complement the information gathered from the literature, primary data were also collected, and a questionnaire based on the