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How benchmarking can support the selection, planning and delivery of nuclear decommissioning projects

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Abstract

Nuclear Decommissioning Projects and Programmes (NDPs) are jeopardized by several risks, long schedule and costs estimates that lay in the range of hundreds of billions of pounds. Moreover, in some countries, these estimates keep increasing and key stakeholders have a limited understanding of the determinants that engender this phenomena. Benchmarking refers to the process of comparing projects in order to identify best practices and generate ideas for improvement. However, even if it is the envisaged approach to tackle the decommissioning challenges and due to the NDPs' uniqueness, until now, benchmarking has been only partially used. This paper proposes an innovative approach to benchmark decommissioning projects, both from the nuclear and non-nuclear industry, within the UK and worldwide. From this cross-sectorial and cross-country analysis, it is possible to gather a list of key NDPs' characteristic and statistically test their correlation with the project performance. The ultimate aim of the research underpinning this paper is to investigate the possible causation between the NDPs' characteristics and the NDPs' performance and to develop guidelines to improve the selection, planning and delivery of future NDPs.

Keywords

Decommissioning, Nuclear legacy, Benchmarking, Risk Management, Statistical Analysis.

Highlights

- Nuclear Decommissioning is affected by several risks and uncertainties
- Decommissioning schedule and cost estimates are hard to predict and rarely reliable
- Benchmarking is the envisaged approach to tackle the decommissioning challenges
- This paper presents an innovative methodology to benchmark NDPs
- Performance measurement is key to implement this methodology

1 Introduction

Nuclear decommissioning is a long, expensive and complex process with a multidisciplinary nature (Laraia 2012a). Its scope is defined by the International Atomic Energy Agency (IAEA) as "*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 2016a).

However, the scope definition of "nuclear decommissioning" is not internationally agreed, which explains why the translation of this term in different languages is generally inadequate. Laraia (2012a) defines decommissioning as the "*administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility and to restore the site to new use".* The World Nuclear Association (WNA 2015) states that "*the term decommissioning includes all clean-up of radioactivity and progressive dismantling of the plant"* and that *"for practical purposes it includes defueling and removal of coolant"*. Conversely, the US Nuclear Regulatory Commission (NRC 2016) strictly defines the start of nuclear decommissioning "*after the nuclear fuel, coolant and radioactive waste are removed".* The IAEA (2016a) focuses on the end of decommissioning and points out that it "*typically includes dismantling of the facility […] but this need not to be the case".* In the UK, the Office of Nuclear Regulation (ONR 2015) provides advice on when to consider operations to cease and decommissioning to start, and considers waste management to be an integral part of decommissioning and dismantling, since (in terms of the process) they cannot be separated, and costs need to be appraised together.

At first sight, this lack of agreement in the definition of "nuclear decommissioning" might seem a mere semantic issue, however, it significantly impacts on the project scope and consequently on the budget and schedule of Nuclear Decommissioning Projects and Programmes (NDPs). For instance, spent fuel (Lawless et al. 2014) and high-level-waste management (Kermisch et al. 2016) have a significant impact on the NDPs' budget. Hence, it is necessary to clarify which is the starting and the ending point of the NDP and to highlight when cost estimates for "nuclear decommissioning" and "waste management" are evaluated together, as in (OECD/NEA 2012).

Additionally, due to the lack of sufficient data regarding completed NDPs, the difficulty in gaining appropriate information, and the overall NDPs' uniqueness in term of complexity and variety, there is a huge gap in the literature concerning benchmarking of NDPs. Therefore, even if benchmarking is the envisaged approach to tackle the decommissioning challenges, it has only been partially used in the nuclear decommissioning sector.

This paper aims to fill this gap with a methodology based on benchmarking to:

- Establish the criteria to evaluate the performance of NDPs from the project management perspective, according to the different type of NDPs, timescales and stakeholders, as suggested by (Turner & Zolin 2012);
- Assess the statistical correlation (and the possible causation) between the NDPs' characteristics and the NDPs' performance;

- Ultimately develop guidelines to improve the project management performance of future NDPs.

The final aim of this research is to gain a critical understanding of the statistical correlation between NDP characteristics and NDP performance in order to develop new knowledge concerning the management of NDPs. This will enable the drafting of empirically-based guidelines and to establish sustainable improvement objectives to support the selection, planning and delivery of future NDPs.

This paper firstly describes the challenges of the decommissioning industry, with a focus on NDPs. Secondly, it investigates the benchmarking analysis applied to the construction industry and explains the case selection. Finally, it presents a deep reflection on the way forward for the adaptation of benchmarking on the nuclear decommissioning industry.

2 Challenges in the delivery of nuclear engineering projects

2.1 Project management challenges in the nuclear industry

At the end of 2015, 439 Nuclear Power Plants (NPPs) were in commercial operation in the world, accounting for a total installed capacity of 380 GWe (IAEA 2016b). However, despite more than 500 NPPs and a number of other nuclear facilities have been built throughout the 20th century, their construction is still an enormous challenge and their successful completion is still hindered by a number of uncertainties and risks. This causes significant schedule slippage and relevant increase of the original budget (Sovacool et al. 2014; Locatelli & Mancini 2012; Ruuska et al. 2011; Ross & Staw 1993).

Conversely, the number of completed NDPs is negligible, being only 16 NPPs and a limited number of other nuclear facilities fully decommissioned in the world (OECD/NEA 2016). Therefore, the information available to the management regarding past experiences is still limited and fragmented (see the assessment of dismantling steam generators in (Hornacek & Necas 2016)), and NDPs' uncertainties can be even higher that the ones of nuclear new build.

2.2 Project management challenges in the nuclear decommissioning industry

Globally, the cost estimates for decommissioning projects lie in the range of hundreds of billions of pounds. In Europe, 77% of the NPPs in shut-down state were located in the UK, France and Germany (Öko-Institut 2013), and the highest figures are related to the decommissioning of Sellafield (UK), where the total cost currently reaches £ 53.2 billion (NDA 2016), accounting for more than half of the decommissioning costs of the nuclear facilities in the entire country. Sellafield is a nuclear fuel reprocessing, waste management and decommissioning site, and it incorporates two First Of A Kind (FOAK) NPPs: the Windscale advanced gas-cooled reactor which is currently undergoing decommissioning and dismantling, and Calder Hall which is awaiting decommissioning and dismantling. In addition, many other facilities on Sellafield site and across the UK are undergoing preparations to be decommissioned. In France, cost estimates for nine reactors to be decommissioned reach more than £ 2.5 billion (CdC 2012), that represents approximately 43% of their construction costs (Öko-Institut 2013). In Germany, the decommissioning costs for the Greifswald reactors add up to around £ 0.7 billion (Öko-Institut 2013).

Moreover, not only the estimated costs for NDPs are very high, but are also a lot higher than comparable non-nuclear decommissioning projects. This difference is sometimes referred to as "nuclear premium", as it includes all the additional costs that NDPs have to face but other decommissioning projects do not have to bear. These additional costs are usually related with radiological hazards and safety & security requirements, but also may be due to the fact that people that work in the nuclear industry need to be more focused on quality and therefore might earn more than colleagues in non-nuclear sectors. Indeed, the report by the Oxford Economics (2013, p.48) states: "*Given the focus on quality and skills, it is reasonable to assume that these activities will also command a premium over and above the same activities in non-nuclear sectors*". According to the Oxford Economics (2013), the nuclear premium ranges between 10% for professional-services-related activities and 20% for manufacturing activities. This exemplifies that NDPs are characterized by high and highly variable costs, long schedule and a range of risks that in many countries are even more significant than the nuclear new build. Also, the average budgets for some of these NDPs keep increasing (NEA/RWM 2011), and key stakeholders have a limited understanding of why this happens.

NDPs are also hindered by the fact that the number of NPPs that have been fully decommissioned is negligible in comparison with the number of facility that have been built throughout the last century. This is due to three main reasons:

- Early NPP were designed for a life of 30 years (WNA 2015), but several factors such as bad knowledge management, loss of knowledge, NPPs not designed to be decommissioned, and early tendency in preferring the deferred dismantling strategy (e.g. in France) caused the postponement of the beginning of the decommissioning (Laraia 2012b);
- Newer NPPs have been designed for a life of 40 – 60 years (WNA 2015), so the majority of the NPP installed have not reached the end of their forecasted lifecycle yet;
- Some nuclear facilities have benefited from a lengthening of their operating licence.

Besides, due to the technical variety and complexity of nuclear facilities, NDPs are characterized by unique characteristics, which continuously raise new concern on how to tackle upcoming decommissioning challenges. The NDPs' uniqueness is caused, for instance, by:

- National policies and administrative requirements (OECD/NEA 2010a);
- The long duration of the project and remote siting of the nuclear facility that created a unique surrounding community that strongly relies on the activities of the nuclear facility itself;
- The fact that (I) at the end of a NDP, no revenues-generating-assets are created, which is what normally occur in the presence of capital projects. In fact, the ultimate goal of a NDP is the remediation of a site to brown field or green field suitable for next use, but the end of the NDP is not directly connected to a stream of revenues. Therefore the incentives to conclude the project on time are not driven by any future expected income; (II) capital projects are normally driven by the urgency of being completed within a certain timeframe (e.g. the London Olympics), while NDPs are not characterized by similar schedule constraints.

In summary, NDPs are not only characterized by technical challenges, but also administrative and socio-economic ones. Moreover, the nuclear decommissioning industry is expected to considerably grow in the next decades, and the number of NDPs in Europe is expected to rise 8% per year (NEI 2016). Therefore an empirically-based methodology based on an inductive cross-case analysis to benchmark NDPs is required. In agreement with Brookes et al. (2015, p.5) who state that "*many lessons-learnt-systems rely solely on unreflective recollections of individuals, and no rigorous attempt is made to discover if characteristics ascribed to the project's performance were actually associated with the ensuing project performance*", this paper proposes a systematic way to investigate NDPs and to systematically compare them in order to transfer the knowledge gained across projects.

3 Benchmarking analysis: a review

The term benchmarking involves *“comparing actual or planned practices, such as processes and operations, to those of comparable organizations to identify best practices, generate ideas for improvement”* and it provides *“a basis for measuring performance”* (PMBOK 2013, p.116). Garnett & Pickrell (2000, p.57) also assert that benchmarking is *“a continuous process of establishing critical areas of improvement within an organization […]”*, that it offers “*the means to identify why `best practice’ organizations are high achievers, and how others can learn from best practice processes to improve their own approach*”, and that has to be “*interactive, team based, flexible but rigorous”.*

Benchmarking within the nuclear decommissioning industry is a much debated topic, as:

- NDPs have “unique” characteristics, as explained in section 2;
- The NDPs’ development embraces several interrelated subjects, such as strategy planning, stakeholder involvement, safety & environmental protection, final purpose, radioactive waste management, and European and Extra-European constraints.

This raises a few challenges regarding how to properly collect, manage and share information, and how to guarantee the reliability of the benchmarking analysis. In the nuclear sector, the OECD/NEA (2015) suggests to perform benchmarking through a comparison with:

- Other studies;
- Decommissioning costing formulae;
- Actual field experiences, and/or other studies.

Therefore, the following sections focus firstly on the implementation of benchmarking (I) in other industrial sectors (e.g. the construction industry), (II) of cost estimates and (III) of empirical NDPs cases, in order to develop a suitable methodology to benchmark NDPs.

3.1 Benchmarking in the non-nuclear sector

In the non-nuclear sectors, benchmarking has already been used to compare projects in order to identify successful projects and the reasons for their success. Within the construction industry for instance, the interests in benchmarking has significantly risen because, finding examples of superior performance, firms can adjust their policies and practices to improve their own performance (El-Mashaleh, M., Minchin, R. 2007; Costa et al. 2006; Ramirez et al. 2004; Garnett & Pickrell 2000).
El-Mashaleh et al. (2007) firstly list and criticize three models that provide insight into overall firm performance for (I) being project specific; (II) not supporting the understanding of the trade-offs among the different variables that affect the performance; (III) providing no insight into the relationship between how resources are expended and the relative success of out- comes; (IV) not allowing the measurement of the impact of certain technological and managerial factors on overall firm performance. Then, these authors present a comprehensive benchmarking model that uses input metrics to determine the company performance, applied on the data collected from 74 construction firms. Garnett & Pickrell (2000) highlight the problems in benchmarking, i.e. (I)

insufficient client resources, time, money, staff, etc.; (II) internal resistance; (III) previous bad experiences; (IV) difficulty in identifying and obtaining partners; (V) difficulty in obtaining data. Also the uniqueness of projects, their various location, the inability of identifying best practices, and the low number of good benchmarks hinders the benchmarking analysis of the construction industry. Costa et al. (2006) compares four benchmarking approaches to use the lessons learned and upgrade the existing benchmarking initiatives and devising new ones. Their final recommendations for future researches are: (I) establish a classification for performance measures, (II) develop frameworks that allow the migration for performance measurement to performance management systems, (III) Develop collaborative learning processes, (IV) devise new measures, (V) develop a theoretical framework for performance management. These researches and suggestions are taken into account for the development of the framework to investigate NDPs.

Additionally, Ramirez et al. (2004) highlight that it is necessary to complement a quantitative benchmarking system with a qualitative based one, in order to establish causal relationships. In their research, Ramirez et al. (2004) present the results from the application of different benchmarking system through different methods: (I) the qualitative benchmarking with the class median, (II) the correlation analysis, (III) the factor analysis, (IV) the multivariate linear regression, and (V) sector trends. These are some of the techniques are listed in Tab 1, that highlight the applicability of different statistical analysis to NDPs.

From these studies, it emerges that the benchmarking analysis is suitable to determine the performance of a company (El-Mashaleh, M., Minchin, R. 2007) and that "*lessons learned from other companies can be used to establish improvement targets and to promote changes in the organization*" (Costa et al. 2006, p.158). Moreover, even if criticised by some authors for its lack of rigour, qualitative benchmarking can enable to compare of management practices, discover relationships between performance data, and determine industry trends. Also, being based on the perception of key personnel, this approach can be applied as part of a continuous improvement programme (Ramirez et al. 2004).

However, there is a need to upgrade existing benchmarking initiatives and devising new ones. Indeed, data collected by El-Mashaleh et al. (2007) refer to hundreds of projects, which allows to perform statistical analysis suitable to big data sets. Therefore, the analysis developed by El-Mashaleh et al. (2007) cannot be directly applied to the nuclear decommissioning industry, due to the low number of completed NDPs. Also, Ramirez et al. (2004) collected data from 42 questionnaires completed by the central office personnel and 87 questionnaires completed by construction site representatives. So, the methodology presented by Ramirez et al. (2004) requires a remarkably larger dataset compared to the number of currently available NDPs. Therefore these analyses cannot be directly applied to the nuclear decommissioning industry. Nevertheless, these studies are extremely valuable and lay the basis of the current research.

Ref	Aim of the research and data collection	Method, model or techniques implemented	Applicable for benchmarking NDPs?
"Benchmarking System for Evaluating Management Practices in the Construction Industry" (Ramirez et al. 2004)	This paper presents the results from the application of the benchmarking system through different methods, i.e. qualitative benchmarking, correlation analysis, factor analysis, multivariate linear regression and sectors trends. Thirteen companies participated to the initial application of the benchmarking system.	(1)**Qualitative benchmarking** with the class median, used to enable each company to evaluate its position compared to the worse and best case scenario and the median. This comparison is highlighted using the Radar graph.	Yes, qualitative benchmarking is suitable between 2 or 3 NDPs. However, it is not suitable to calculate the median (see section 2 that highlight the uniqueness of NDPs).
		(2)**Correlation analysis,** used to investigate the intensity of the linear relationship between two variables, Xi and Xj. To measure this intensity of the correlation, the Pearson's coefficient is used. The Pearson's correlation is a measure of the strength and direction of the linear relationships that exists between two variables measured on an interval scale.	No, as to use the Pearson's correlation, variables should be approximately normally distributed and there should be no significant outliers (Laerd Statistics 2016). Moreover, the cases should represent a random sample from the population. These assumptions are not met by NDPs.
		(3)**Factor analysis**, that uses the principal components to determine the underlying structure among the different management dimensions and identify relationships not previously established.	No, as the principal component analysis requires assumptions (e.g. linearity (Shlens 2005)), that are not met by NDPs.
		(4)**Multivariate linear regression**, that was implemented but discarded due to the weak correlation coefficient caused by the low number of data quantity of data.	No, as assumptions for the multivariate linear regression (e.g. linearity, homoscedasticity, etc.) are not met by NDPs.
		(5)**Sector trends** by management dimensions, by job categories, and by subsectors are used to categorize and analyse survey results.	Yes, as trends highlighted during the descriptive analysis of the collected data can yield interesting conclusions.
"Management of Construction Firm Performance Using Benchmarking" (El-Mashaleh, M., Minchin, R. 2007)	This research presents a comprehensive benchmarking model that uses input metrics to determine the company performance. Data were collected from 74 construction firms through a survey questionnaire.	**Data Envelopment Analysis** (DEA). DEA is concerned with evaluation of the activities of organizations such as business firms, hospital and government agencies. The organization responsible for converting inputs into outputs is called Decision Making Unit (DMU). DEA uses mathematical linear programming to determine which of the DMU forms an envelopment surface, i.e. an efficient frontier.	No, as the number of NDPs and the information available on these NDPs is too low to implement the DEA.
"Power plants as megaprojects: Using empirics to shape policy, planning, and construction management" (Brookes & Locatelli 2015)	This paper investigates the correlation between characteristics of power plant megaprojects and their costs and schedule cost performance.	This research implements the **Fisher Exact Test** to a dataset of o a dataset of 12 case studies from several industries, e.g. the nuclear, coal, and renewable resources. The Fisher Exact Test investigates the correlation of single independent variables vs dependent ones and is able to identify correlations within small data sets.	Yes, as the Fisher Exact Test is able to identify correlations within small data sets (< 30 cases), as it investigates each project characteristics independently.
"Empirical research on infrastructural megaprojects: what really matters for their successful delivery" (Locatelli et al. 2016).	This research investigates the relationship between project characteristics and performance using a pool of 44 case studies.	This paper implements **the Fisher Exact Test** and **Machine Learning** techniques. Machine Learning enable rigorous "pattern spotting" analysis of the existing, relatively small dataset, which did not allow the application of multivariate statistical analysis. Three different learning methods are implemented, i.e.: Decision tree, Naïve Bayes and Logistic Regression.	Yes, both the Fisher Exact Test and Machine Learning are applicable to NDPs. In particular, being the Logistic Regression a type of probabilistic model used to predict the class based on one or more attributes (not necessarily continuous), it can be applied to the case of NDPs.

Tab 1. Techniques for benchmarking

3.2 Benchmarking cost estimates

Decommissioning cost analysis have the purpose of securing funding, preparing a decommissioning plan within the context of licensing and budgeting a baseline for decommissioning implementation (OECD/NEA 2015). However, cost estimates under uncertainty are extremely challenging (Torp & Klakegg 2016), are only reliable when estimation practises are similar (that is not the case of the European, Japanese and American nuclear decommissioning industry (OECD/NEA 2010b)) and when based on a complete, well-planned and regularly updated calculation scheme (Öko-Institut 2013). The OECD/NEA (2012) proposes an International Structure for Decommissioning Costing of nuclear installations, whose application has been spreading quickly, but it is still not internationally adopted.

Indeed, even if a systemic view would be the most suitable approach (Locatelli et al. 2014), many different organizations have performed estimates using several approaches and assumptions, therefore achieving very different results. Tab 2 is particularly interesting as it presents the costs for dismantling reactors in Germany, Belgium, Japan, UK, Sweden and US applied to the EDF PWR fleet in operation. This demonstrates how costs range across countries and vary as a function of different estimation methods. It also highlights that, at least sometimes, estimates are "*too shallow to yield a reliable comparison base for facilities in other countries, of different size and different operating history"* (Öko-Institut 2013, p.65). Tab 2 also highlights that cost estimates in the same country (US and Germany) present a variation range of a factor of two or three depending of the selected methodology used (Öko-Institut 2013).

Countries	**EDF**	**UK**	**Sweden**	**Belgium**	**Germany (4 methods)**	**Japan**	**US (3 methods)**
Extrapolation for 58 reactors	18.1	46	20	24.4	25.8 34.6 44 62	38.9	27.3 33.4 34.2

Tab 2. Extrapolation of the costs of dismantling 58 reactors in € billion in 2010, adapted from (Öko-Institut 2013)

This lack of consistency, both in the number of the unavoidable differences of the nuclear facility and to unforeseen events (OECD/NEA 2010b), makes it difficult both to produce reliable cost estimates (see one example in (Park et al. 2016)) and to compare them. So, due to the complexity of performing a reliable cost analysis also due to the speed at which the cost of single item/activity change, this paper suggests a top-down methodology based on a benchmarking to systematically compare international NDPs.

4 How to benchmark NDPs

The methodology presented in this paper adapts benchmarking to the nuclear decommissioning industry with the purpose to tackle the project management challenges of NDPs. This methodology is based on a top-down approach, which is a way to break-down a system (big picture), gain a better understanding of its sub-systems (detailed components) and find the key drivers of a successful NDPs. The term *top-down* is normally used in opposition to the *bottom-up* technique, where work statement, set of drawings or specifications are used to extract material quantities required for executing each discrete task and to derive direct labour, equipment and overhead costs (OECD/NEA 2012). The aim of the bottom-up approach is to produce cost estimates, as well as best-case and worst-case scenario, while the top-down approach can be applied to define which performance measures are most critical in determining the company's overall success and the factors that have the biggest impact on the project performance.

Stemming from Garnett & Pickrell (2000) and based on the research performed by Brookes & Locatelli (2015), this methodology proposes a five-steps process to support the selection, planning and delivery of NDPs. In their research, Brookes & Locatelli (2015) presented an empirically-based methodology to identify the characteristics of 12 construction megaprojects in the energy sector that correlate with schedule and cost performance. To do this, a list of megaprojects characteristics was collected, and then statistical analysis (i.e. the Fisher Exact Test) was employed to reveal the correlation between a single project characteristic and the project performance. Similarly, the ultimate goal of the current research is to statistically investigate which are the NDPs' characteristics that impact on the NDPs' performance.

As shown in Fig 1, the five steps of this research, are:

1) Research initiation;
2) Data codification;
3) Independent and dependent variable operationalization;
4) Implementation:
    a. detailed cross-comparison;
    b. statistical analysis and data mining;
5) Validation and dissemination.

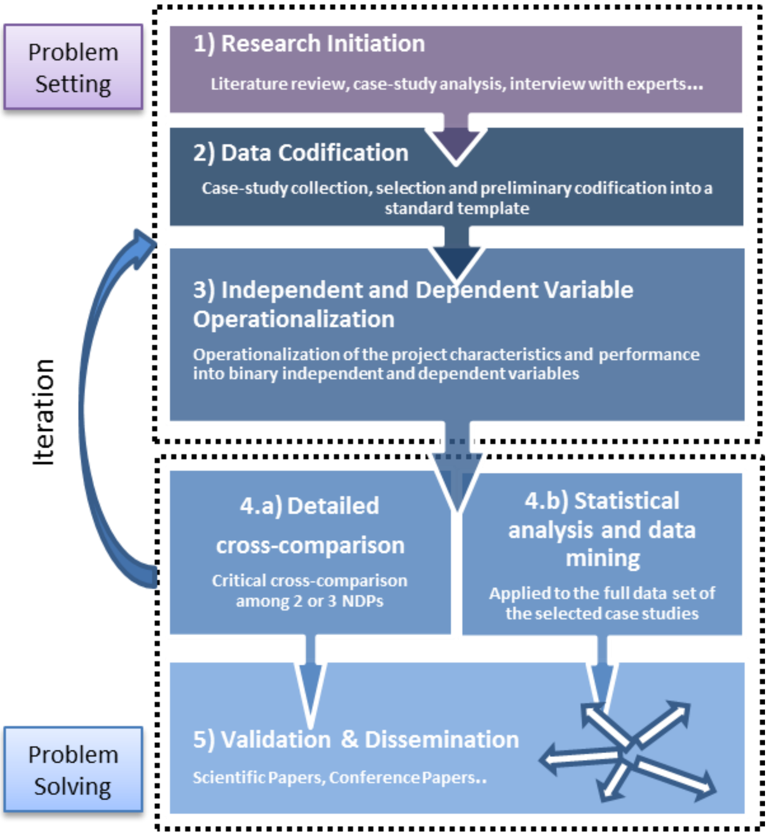

Fig 1. The suggested framework for benchmarking NDPs

The key features of each step are described below:

1) Research initiation

The first step embraces a preliminary literature review regarding nuclear (and eventually non-nuclear) decommissioning projects, case-study collection, semi-structured interviews with experts and site visits. Data regarding NDPs are selected according to their relevance and completeness. The date when they are delivered is also significant, since policies and constraints change with time (usually becoming stricter). The current pool of collected NDPs includes around 30 European NDPs. However, this is a preliminary sample and this number is likely to increase in order to improve the reliability of the results of the statistical analysis.

There are several methods to identify the level of business at which the comparison analysis should take place in order to find suitable NDPs, such as questionnaires and process mapping workshop. However, it is advocated to firstly review the literature about NDPs and then directly interview key decommissioning experts for scoping purposes and to gain a feedback on early results regarding good (and bad practices) during the delivery of previous NDPs. Indeed, the output of the first step is the preliminary collection of lessons learned regarding NDPs' performance drivers, the selection of NDPs and of the techniques for the data analysis.

2) Data codification

Data codification is extremely relevant as publically available descriptions of NDPs can be either hundreds of pages or only few paragraphs. To ease the comparison of NDPs, this research envisages the gathering of both qualitative and quantitative information to be recorded and codified in a standard template. This template groups the NDPs' characteristics into macro-categories, such as an (I) overview of the projects, its physical characteristics and its final end-state; (II) governance, funding and contacting schemes; (III) stakeholders & stakeholder engagement. These macro-categories are based on established frameworks (e.g. the OECD/NEA lists of lessons learned on factors that impact on decommissioning costs (OECD/NEA 2016), the IAEA "*project related influences*" (IAEA 2011), the NDA Critical Enablers (NDA 2011) or others framework (Dimitriou et al. 2013; NEA/RWM 2011; ITRC 2008; Locatelli & Mancini 2010) and can have different levels of details.

The output of this second step is the development and population of a standard templates (for example in the form of a Word table or an Excel file) that allow the cross-comparison of NDPs.

3) Independent and Dependent Variable Operationalization

The benefit of building and using a standard template is not only to ease the comparison between projects, but also to facilitate the systematic collection for subsequent operationalization of the NDPs' characteristics (the independent variables) that impact on the NDPs' performance (the dependent variables).

NDP performance can be assessed through project-specific indicators. Indicators are measures of the project status, used to reveal what is actually going on at any particular time and in any particular aspect of the project. Moreover, these indicators could facilitate an appropriate control of the project, in terms of time, money, safety, environmental issue, etc. and they can be used to (I) measure the progress of the project, (II) give a measure of the project performance, (III) enable comparison between projects, (IV) communicate with stakeholders (IAEA 2011). In this paper, the focus is on the NDPs' cost performance, but this methodology can be applied on other aspects of the delivery of NDPs, e.g. health, safety, security and environmental performance (IAEA 2011) or social-acceptance performance (Invernizzi et al. 2017b).

The OECD/NEA (2010b) focuses on cost aspects and classifies key costs elements into "*very significant*" and "*moderately significant*", while in 2003 "*significant cost drivers*" where listed (OECD/NEA 2003). These are presented (on the left side) in Tab 3. On the right column, the correspondent independent variables are operationalized. Other NDPs' characteristics require a more qualitative approach to be operationalized. Understandably, the length of the list of NDPs characteristics increases with the increase of the NDP level of detail and the data and information available, and can therefore be considerably long (>100 NDPs' characteristics).

	Relevant cost element, as in (OECD/NEA 2010b) **and** (OECD/NEA 2003)	**Main correspondent independent variables, as operationalized in the current research**
“Very significant” cost element, as in (OECD/NEA 2010b)	➢ Scope definition and changes to the project plan ➢ Clean structure disposition and disposal of the site for new developments ➢ End-point state and disposition of wastes ➢ Waste storage and the availability of ultimate disposition facilities ➢ Disposition of spent nuclear fuel and on-site storage prior to a permanent repository	➢ The end state has restricted/UN-restricted use & buildings/NO buildings
		➢ The final scope of the NDP includes the commercial reuse of the existing facility/facilities
		➢ There is LLW/ILW/HLW interim storage/storage/repository on site and/or in the country
		➢ There is a reprocessing facility on site and/or in the country
		➢ The nuclear site hosts some facilities that are still operating while the NDP takes place and/or manage radioactive material from other sites in the same country and/or from other countries
	➢ Regulatory changes and increased requirements for additional information and detail	➢ The NDP was affected by regulatory changes/increased requirements/loosening of requirements
	➢ Site characterisation of physical, radiological, and hazardous materials inventory	➢ Extensive characterization of the full site was planned/possible/performed and/or resulted to be accurate
	➢ Availability of experienced personnel with knowledge of the relevant plant	➢ External consultants and/or experienced managers have been employed
		➢ The case study is a FOAK at a site level and/or country level and/or global level
		➢ The facility started construction before 1960/1970/1980/1999/2000
	➢ Assumed duration of the dismantling and clean-up activities	➢ The decommissioning activities are estimated to last 5, 10, or more than 10 years
	➢ Contingency application and use in estimates to account for uncertain events	➢ Contingency Level: > or < than 10%,20%, 30%[1]
“Significant cost drivers” as in (OECD/NEA	➢ Type and size of the reactor	➢ The case study is a multi-facility/a NPP/research facility
	➢ Number of units on the site	➢ The case study consists of a group of facilities or a single facility
	➢ Operating history of the plant	➢ The facility has experienced a nuclear accident equal to 1-3 or 4-5 in the International Nuclear Event Scale (INES)

Tab 3. Relevant cost elements from (OECD/NEA 2010b; OECD/NEA 2003) and their operationalization in the current research

The output of the third step is the collection of the NDPs’ independent and dependent variables and their operationalization into binary variables for the subsequent statistical analysis. The dependent and independent variables operationalization, which consists of coding real data (quantitative, qualitative, complex and uncertain) into “*formalised constructs*” (as defined by (Lee & Lings 2008)) for the statistical analysis is the most challenging part of the methodology. Indeed, some variables, such as the location and physical characteristics of the NDP, can be operationalized into constructs in a “non-arbitrary way” through concrete objects and attributes as in (Rossiter 2002), while the

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[1] The OECD/NEA (2010b) defines contingencies as “*unforeseeable elements of cost within the defined project scope”*. Conversely, uncertainties also cover “*unforeseeable elements outside the defined project scope, or changes in the scope of the project as defined”*

definition of others NDPs' characteristics, such as the stakeholders' engagement, requires a mix of qualitative and quantitative information.

4) Implementation.

The fourth step consists of the actual data analysis, which is split into two stages, i.e. a detailed qualitative & quantitative cross-comparison and statistical analysis & data mining, respectively 4.a. and 4.b in Fig 1. Step 4.a highlights the good and bad practices that empirically resulted to be relevant for the successful performance of a NDP. The statistical correlation of these practices, together with "lessons learned" gathered from published literature (e.g. journal articles, official reports, case studies, etc.), interviews with experts, site visits and questionnaires is then investigated in step 4.b. The cross-comparison of case studies of step 4.a needs to be performed both within the UK and not, both within the nuclear industry and not, as shown in Tab 4. Indeed, benchmarking projects across different countries and different industrial sectors will support the sharing of lessons learned that could be applied on UK NDPs.

	Nuclear	**Non-nuclear**
UK	(1) Benchmarking nuclear decommissioning projects across the UK	(3) Benchmarking non-nuclear decommissioning projects across the UK
Non -UK	(2) Benchmarking nuclear decommissioning projects across several countries	(4) Benchmarking analysis across countries and in different industrial sectors

Tab 4. Comparisons on decommissioning projects

In particular:

- The aim of the investigation of NDPs within the UK is to encourage the sharing of knowledge gained with past experiences across the country and avoid finding "the same solution twice";
- The international analysis of NDPs enables the gathering of lessons learned from similar NDPs outside the UK;
- The comparison of decommissioning projects form the non-nuclear sector (e.g. the Oil & Gas decommissioning industry) promotes the collection of best practices that could be applied to future NDPs.

The statistical analysis of step 4.b needs to address (I) the complexity and variety of NDPs, (II) the low number of completed NDPs, (III) the limited information available on the ongoing NDPs, or, in other words, their uniqueness. Tab 1 in section 3.1 provides a review of different studies that applied statistics for benchmarking purposes. This table highlights that many of these have to be rejected as not suitable for the investigation of NDPs. The Fisher Exact Test is suitable since (Brookes & Locatelli 2015; Freeman & Campbell 2007):

- It is a non-parametrical statistical significance test, i.e. it does not make assumptions about distributions;

- It uses categorical data in the form of a contingency table, and is used for categorical binary data;
- It is an exact test, i.e. the probability of a relationship existing between the variables can be calculated exactly.

The Fisher Exact Test is therefore implemented first. The Fisher Exact Test is able to identify correlations within small data sets (Leach 1979), e.g. 20-30 projects and to evaluate whether or not a single independent variable is associate with the presence (or absence) of a dependent variable, using categorical data in the form of a contingency table as input. The output of the test is a p-value, which represents how likely it is that the result detected by the implementation of this statistical analysis could have resulted from chance rather than due to a real relationship between the variables in question. In this respect, the smaller the "p-value", the better. Key features, limitations and the implementation of the Fisher Exact Test applied to energy megaprojects can be found in (Brookes & Locatelli 2015; Locatelli et al. 2017). Regarding the value of the p-values, the authors suggest to adopt a higher significance level than the one traditionally used, such as a p-value < 0.15 rather than a more typical value of p-value <0.05. This means that statistically significant findings must be dealt in a circumspect fashion and that the actual causation between project characteristics and their performance would require further investigation (step 5), e.g. through interviews with experts. The Fisher Exact Test also presents some limitations, such as the fact that it tests every variable by itself, and it cannot assess whether the combination of two independent variables have an impact on the performance of the project or not. To address these limitations, other statistical methods (such as the Qualitative Comparative Analysis (Schneider & Wagemann 2012), Logistic Regression (Mehta & Patel 1995) and data mining techniques) will be implemented as a follow-up of the current study.

Step 4.a and 4.b are intrinsically related, and both support the identification of good (and bad) practices to improve the selection, planning and delivery of NDPs. Step 4.a is here exemplified through the detailed cross-comparison between Rocky Flats (US) and Sellafield (UK) (Invernizzi et al. 2017a). These two NDPs have been selected because they are both recent NDPs, have a comparable physical size, had a decommissioning budget in the order of dozens of billions of dollars and share a reasonably similar history (e.g. both facilities were opened for military purposes in the 1940s/1950s and have been affected by major nuclear accidents). Moreover, there are publically available information in English regarding both these NDPs. Nevertheless, these NDPs have also very different aspects. Rocky Flats was a military nuclear weapons facility that produced plutonium and enriched uranium from 1953, and stopped operations 1989. It was owned by the Department of Energy (DOE) and was managed by a series of weapons contractors. Moreover, during its decommissioning, its waste was shipped to other states in the US. Conversely, Sellafield is still an operating nuclear site that handles radioactive material shipped both from other UK nuclear sites in the UK and other countries worldwide.

When Rocky Flats was shut down in 1989, due to the significant radioactivity on site, the US DOE estimated it would have taken 70 years and $ 36 billion to decommissioning it. The project was however completed safely by a joint venture in less than 10 years and $ 3.5 billion (DOE 2013;

Cameron & Lavine 2006; Bodey 2006). Sellafield, a 6 km^2 UK nuclear site that contains 99% of the UK radioactivity, is estimated to take more than 100 years and £ 53 billion to be decommissioned (NDA 2016; Sellafield Ltd 2016).

Even if these two NDPs are remarkably different, their cross-comparison highlights the importance of several NDPs' characteristics (Invernizzi et al. 2017a). Within the others:

- **Funding arrangements and contracting schemes, especially if tailored on single employees.** Indeed, Rocky Flats adopted the so-called "*abundance approach*", where the aim was to fill the gap between forecasted (successful) performance and "*spectacular*" performance, i.e. to achieve positive deviance by closing the abundance gap (Cameron & Lavine 2006). This, together with incentives singularly allocated to employees to promote feasible ideas can support the performance of the NDP.
- **The size of the free space available within the perimeter of the nuclear site to manage radioactive waste**. In fact, even if the size of Rocky Flats is, in some ways, comparable to Sellafield, Rocky Flats had a "buffer zone" which surrounded the site that resulted to be helpful for the management of radioactive material (Cameron & Lavine 2006). Sellafield, on the contrary is "*packed with buildings*" (informal talks with NDA and Sellafield employees), which hinders the construction of new facilities to treat and confine the radioactive material.
- **Early and timely engagement of stakeholders.** Indeed, effective communication and the involvement of stakeholders in collaborative action support the smooth delivery of the project.

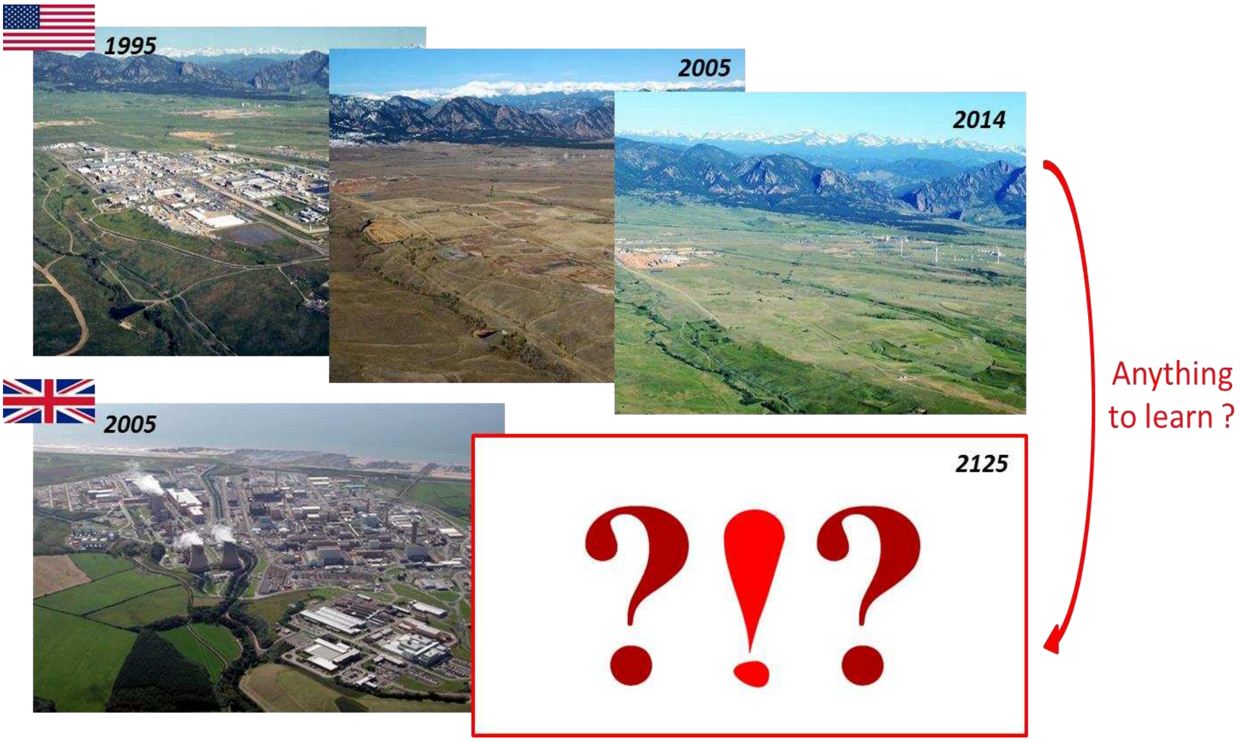

Fig 2. Rocky Flats NDP vs Sellafield NDP

Step 4.b. is exemplified in Tab 5, showing the results of four NDPs' characteristics tested through the implementation of the Fisher Exact Test on a pool of 30 European NDPs.

Independent variables, i.e. the NDP characteristics	**Correlation of the independent variables with the dependent variable "50% cost overrun"**
The country scores a corruption perception index > 60[2]	The fact that the corruption perception index in a country is less than 60 is correlated with **the presence** of 50% of cost overrun. The p-value is lower than 10%, showing a correlation.
The legal timeframe for review of decommissioning plans is less 2 years	The fact that the legal timeframe for review of decommissioning plans is less 2 years is strongly correlated to **the absence** of 50% of cost overrun. The p-value is lower than 10%, showing a correlation.
There are other nuclear facilities still operating in the country	The fact that there are other nuclear facilities operating in the country **is not correlated** to the absence of 50% of cost overrun. The p-value is >>15%, showing no correlation.
The NDP is state owned	The fact that the NDP is state owned **is not correlated** with the absence of 50% of cost overrun. The p-value is >>15%, showing no correlation.

Tab 5. Example of independent variables statistically correlated to 50% cost overrun

5) Validation and dissemination

Validation of the methodology through its application to pilot projects and dissemination of the results are the last step of the proposed framework to investigate NDPs. The dissemination process is a way to share the body of knowledge acquired and to discuss the results obtained. This would also be a way to increase the participation into collaborative projects. The output of this step is the publication of scientific papers, the presentation of the results to conferences and to other organized events.

Lastly, it is important to underline that, in this analysis, iteration is fundamental. Indeed, greater the number of case studies selected, analysed and codified, greater the probability not to omit or neglect any relevant NDPs' characteristics that impact on the NDPs' performance. Also, the implementation of this analysis cannot be treated as a "closed" system: in fact, as it is based on the codification of the real world into mathematical models, it is necessary to continuously add new inputs and validate the results.

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[2] From Transparency International, as in (G. Locatelli et al. 2016)

5 Conclusion

In the next decades, more and more energy infrastructure will need to be dismantled and, due to the technical variety and complexity of NDPs, the nuclear decommissioning industry faces the biggest risks and uncertainties. NDPs are characterized by long schedule and highly variable costs that lie in the range of hundreds of billions of pounds. Moreover, these estimates keep increasing and key stakeholders have a limited understanding regarding why this happens. Also, due to specific NDPs' challenges and the uniqueness of NDPs, it is extremely challenging to benchmark NDPs.

Therefore, this research suggests a top-down approach based on benchmarking to assess the statistical correlation and understand the possible causation between the NDPs' characteristics and their performance. This paper provides an original framework to collect, select and operationalise case studies into independent and dependent variables, i.e. respectively the NDPs' characteristics and their performance. This five-step framework for benchmarking NDPs is innovative as it combines qualitative and quantitative cross-case study and statistical analysis (e.g. the Fisher Exact Test) into an iterative process. Indeed, two parallel but intersected analysis are envisaged: the first one is a detailed comparison between 2 or 3 case studies, selected both form the nuclear and non-nuclear industry, both within the UK and globally; the second one is the statistical analysis where the Fisher Exact Test is firstly applied to highlight the statistical correlation between the NDPs' characteristics and their performance. These two analyses are intrinsically related, and both support the identification of best practices to establish improvement objectives within the nuclear decommissioning industry. Other statistical analysis and data mining techniques that embrace NDPs aspects that we have not stressed in this paper (e.g. safety and security) are a follow-up of this research and will be implemented iteratively, to achieve a higher grade of confidence in the results.

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