Benchmarking Nuclear Decommissioning

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The candidate confirms that the work submitted is her own, except where work has formed part of jointly authored publications. The contribution of the other authors in the jointly authored publications included in this work has been explicitly indicated. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

This thesis is following the "Protocol for the format and presentation of an alternative style of doctoral thesis including published material" by the Faculty of Engineering of the University of Leeds.

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Abstract

Historically, project management research on infrastructure has mostly focused on its planning, design, and construction. However, globally, more and more infrastructure, such as nuclear and offshore oil & gas facilities, are reaching the end-of-life and will soon need to be decommissioned. Decommissioning projects are a new, emerging, unavoidable challenge that project managers are currently facing and will face more and more severely in the future. Primarily due to the relevance of the nuclear sector, this research focuses on Nuclear Decommissioning Projects and Programmes (NDPs), intended as site-level endeavours. NDPs are long and complex projects, whose estimates reach billions. Moreover, the cost estimates of several of these projects keep increasing while there is a limited understanding of why this happens. Triggered by these considerations, this industry-funded research develops and applies a methodology based on benchmarking to investigate the NDP characteristics that affect the NDP performance in terms of cost and time. Due to the NDP small sample size, the limited number, availability of and reliability of data and information on NDPs, and the extremely limited previous research on NDPs, inputs of this research are both secondary data and information, as well as primary ones collected through interviews with experienced practitioners. Outputs of this research include a methodology based on benchmarking that incorporates both qualitative and quantitative analysis, and as well as its application on NDPs. However, this methodology could be applied to other industrial sectors as well. The contribution of this thesis is both methodological and practical as it both develops and applies a methodology to investigate NDPs, highlighting the NDP characteristics that affect the NDP performance to ultimately improve the selection, planning, and delivery of NDPs. Moreover, by introducing the topic of NDPs to the project management community, this thesis lays the path for a number of future research, both in order to address the limitations of the current research, e.g. its focus on European NDPs, as well as to promote the in-depth investigation of each single NDP characteristics that emerged during this study.

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List of abbreviations

- BIM: Building Information Modelling
- CEN: Compensation Event Notification
- CEQ: Compensation Event Quotation
- D&D: Decommissioning & Dismantling
- DEA: Data Envelopment Analysis
- DMU: Decision Making Unit
- DOE: Department of Energy
- EC: European Commission
- EPOC: Engineering Project Organization Conference
- EURAM: European Academy of Management Conference
- EVM: Earned Value Management
- EW: Early Warning
- EWN: Early Warning Notice
- FEED: Front End Engineering and Design
- FOAK: First of A Kind
- GDP: Gross Domestic Product
- IAEA: International Atomic Energy Agency
- ICE: Institution of Civil Engineers
- ICONE: International Conference on Nuclear Engineering
- IEF: International Expert Feedback
- IJMPB: International Journal of Managing Projects in Business
- IJPM: International Journal of Project Management
- ILW: Intermediate Level Waste
- IRNOP: International Research Network on Organizing by Projects
- ISDC: International Structure for Decommissioning Costing
- LLW: Low Level Waste
- LTC: Long-Term Client
- NAO: National Audit Office
- NDA: Nuclear Decommissioning Authority
- NDPs: Nuclear Decommissioning Projects and Programmes
- NEA: Nuclear Energy Agency
- NEC: New Engineering Contract
- NIMBY: Not in My Back Yard

- NOD: Notification of Defect
- NPPs: Nuclear Power Plants
- NRC: Nuclear Regulatory Commission
- nWOM: Negative Word of Mouth
- OECD: Organisation for Economic Co-operation and Development
- ONR: Office for Nuclear Regulation
- PBC: Project-Based Company
- PMBOK: Project Management Body of Knowledge
- PMI: Project Management Instruction
- PNE: Progress in Nuclear Energy
- PP&C: Production Planning and Control
- QCA: Qualitative Comparative Analysis
- RQ: Research Question
- VM: Value Management
- WNA: World Nuclear Association

List of publications included in this thesis and my contribution

This section lists the publications included in this thesis, splitting them into the ones in section B, and the ones in the Appendix. The papers included in section B have been selected as they meet the requirements for the alternative style of the University of Leeds doctoral thesis, their relevance and their current publication status. The papers included in the Appendix are respectively a conference paper and a short paper, which therefore do not meet the requirements for the alternative style of the University of Leeds doctoral thesis. However, they are included as they laid the groundwork for the other publications, in this way supporting the overall research development.

Papers in the main body of the thesis

I. Invernizzi, D. C., Locatelli, G., and Brookes, N. J. (2018), "*A methodology based on benchmarking to learn across megaprojects: the case of nuclear decommissioning*", International Journal of Managing Projects in Business (IJPMB), 11(1), 1–18.

As first author of Publication I, I reviewed the literature on benchmarking, detailing inputs and outputs of each step of the methodology based on benchmarking developed for this PhD research, and thirdly by exemplifying its application in the paper. I wrote the first version of the paper, which was originally submitted, accepted, presented and discussed in EURAM2017. The paper was selected by the editor of IJPMB before it was presented to EURAM to be published in IJPMB, provided minor changes following the reviewers' comments were included. Dr Giorgio Locatelli provided valuable guidance during the framing of the early phase of this research. Prof Naomi J Brookes also commented on the draft of this paper. My contribution to the paper was approximately 85%.

II. Invernizzi, D. C., Locatelli, G., and Brookes, N. J. (2017), "*Managing social challenges in the nuclear decommissioning industry: A responsible approach towards better performance*", International Journal of Project Management (IJPM), 35(7), 1350–1364.

As the first author of Publication II, I was responsible for the planning of the research design, collecting and analysing the data, and writing the first version of the paper. The detailed comments from four anonymous reviewers strongly influenced the final version of the paper. I was responsible for amending the paper following the reviewers' comments. Dr. Giorgio Locatelli provided valuable support especially during the revision process of the paper. Prof Naomi J Brookes provided feedback on the writing of the paper. My contribution to the paper was approximately 90%.

III. Invernizzi, D. C., Locatelli, G., and Brookes, N. J. (2018), "*Characterising nuclear decommissioning projects: An exploration of the end-of-life of nuclear infrastructure"* – Submitted to Construction Management and Economics

As the first author of Publication III, I was responsible for planning the research design, collecting and analysing data and information both from secondary data and semi-structured interviews, transcribing the interviews, analysing them and writing the first draft of the paper. Dr. Giorgio Locatelli provided valuable comments during the development of the research and concerning the first draft of the paper. Prof Naomi J Brookes commented on the writing of the paper. My contribution to the paper was approximately 85%.

IV. Invernizzi, D. C., Locatelli, G., and Brookes, N. J. (2018), "Exploration of the Relationship between Nuclear Decommissioning Projects Characteristics and their Cost Performance", Progress in Nuclear Energy (PNE), 110, pp.129–141.

As the first author of Publication IV, I was responsible for planning the research design, collecting and analysing the data, selecting and applying the suitable statistical tests to analyse the data, and writing the first draft of the paper. The comments from two anonymous reviewers during the first revision influenced the final version of the paper. Dr. Giorgio Locatelli provided valuable comments during the development of the first draft of the paper. Prof Naomi J Brookes commented on the writing of the paper. My contribution to the paper was approximately 90%.

V. Invernizzi, D. C., Locatelli, G., and Brookes, N. J. (2018), "*The need to improve communication about scope changes: frustration as an indicator of operational inefficiencies*", Production Planning and Control (PP&C), (May), 1–14.

As the first author of Publication V, I was responsible for planning the research design, collecting and analysing the data, and writing the paper. This publication is based on my experience as an intern in a project-based company involved in the decommissioning industry as a major contractor. I wrote the first draft of the paper. The detailed comments from two anonymous reviewers during the first revision influenced the final version of the paper. The comments of a third anonymous reviewer during the second revision of the paper were minimal, but also influenced the last version of the paper, helping to increase its quality to the required standard. I was responsible for amending the paper following the reviewers' comments. Dr. Giorgio Locatelli provided valuable feedback during both the development of the first draft of the paper and during the revision process. Prof Naomi J Brookes provided feedback on the writing of the paper. My contribution to the paper was approximately 95%.

VI. Invernizzi, D. C., Locatelli, G., Gronqvist, M., and Brookes, N. J. (2018), "*Applying value management when it seems that there is no value to be managed: the case of nuclear decommissioning*" – Published in IJPM, available online since the 28th January 2019

As the first author of Publication VI, I was responsible for planning the research design, collecting and analysing data and information both from secondary data and semi-structured interviews, transcribing the interviews, analysing them and writing the first draft of the paper. The detailed comments from four anonymous reviewers during the first revision strongly influenced the final version of the paper. Dr. Giorgio Locatelli provided valuable comments during the development of the first draft of the paper. Mr. Marcus Gronqvist reviewed the draft paper as well, providing valuable feedback and commenting on the writing paper. Prof Naomi J Brookes commented on the overall research design and on the writing of the paper. My contribution to the paper was approximately 85%.

Papers in the appendix of the thesis

a. Invernizzi, D.C., Locatelli, G., Brookes, N.J. and Grey, M. (2017), "*Similar but different: a top-down benchmarking approach to investigate nuclear decommissioning projects*", paper accepted presented at the International Conference on Nuclear Engineering, ICONE25, July 2017, Shanghai.

As the first author of Publication [a], I was responsible for the selection of the two cases, planning the research, collect the information for the cross-comparison and writing the first version of the paper. The findings and the feedback received from this preliminary cross-comparison were fed into the subsequent steps of the research. Dr. Giorgio Locatelli provided valuable support during the structuring of this paper. Prof Naomi J Brookes commented on the writing of the paper. Mr. Martin Grey commented on the correctness of the information and on the writing of the paper. My contribution to this paper was approximately 90%.

b. Invernizzi, D.C., Locatelli, G. & Brookes, N.J., 2018. "*Cost overruns - Helping to define what they really mean"*, Proceedings of the Institution of Civil Engineers, Civil Engineering, 171(2).

As the first author of Publication [b], I was responsible for triggering the discussion around the lack of clarity in the definition of "cost overruns" and writing the first draft of the paper. Dr. Giorgio Locatelli provided valuable support during the structuring and writing of the paper. Prof Naomi J Brookes commented on the writing of the paper. My contribution to this paper was approximately 85%.

The journal publications and conference publications published or presented in national and international conferences but not included in this thesis is listed in section D.2.

Current status of the papers

The current status of the six publications in the main body of the thesis is as follows:

- Publication I – published
- Publication II – published
- Publication III – submitted
- Publication IV – published
- Publication V – published
- Publication VI – published

The current status of the papers in the appendix of this thesis is as follows:

- Publication a - presented in ICONE 2017
- Publication b - published

Structure of this thesis

This thesis consists of four parts:

- PART A, i.e. the introduction of the thesis, briefly illustrates the research background, derives the overall research aim and objectives, explains the research development and presents the overall research design;
- PART B consists of the publications I, II, III, IV, V and VI, each of them addressing one of the research objectives introduced in Part A, and therefore contributing to the achievement of the overall research aim;
- PART C, i.e. the overall discussion and conclusion of this thesis, highlights the contribution to knowledge of this research, summarizes the achievement of the research objectives, also suggesting a path for future research;
- PART D, i.e. the appendix, is split into two. Section D.1 collects publications [a] and [b], which are supplementary pieces of research, relevant during the development of this research. Section D.2 lists the work done in relation to this PhD research but not included in the main body of this thesis.

A. Introduction

A.1 Research background

A.1.1 Decommissioning: a new, emerging challenge for project managers

The majority of the project management research on energy infrastructure has investigated the planning, design, and construction of infrastructure, and until now, only limited attention has been put on the end-of-life of energy infrastructure and its decommissioning. Decommissioning refers to the end-of-life of a facility and to the process of withdrawing it from service, taking it apart and deconstructing it. Specifically when discussed within the nuclear industry, "decommissioning" is defined as *"all the administrative and technical actions taken to allow the removal of some or all the regulatory controls from a facility […]"* (IAEA 2017).

Decommissioning is a relevant issue for energy infrastructure, as energy infrastructure that has been built throughout the last century will soon reach its end of operational life, and will need to be decommissioned for a number of interconnected reasons, embracing safety, security ethical, moral and regulatory-related reasons. Hence, the array of energy infrastructure that is approaching its end of life is rapidly growing, causing the rise of a number of interrelated challenges. Therefore, both academics and practitioners will need to deal more and more extensively with the challenges of decommissioning projects, requiring the management of a number of stakeholders with different perspectives, backgrounds, and goals.

Decommissioning projects are the new, emerging, global, unavoidable challenge that project managers will face more and more in the future. For example, regarding the hydroelectric sector, Oldham (2009) reports that in the US there are 79,000 "significant dams", but that only 600 (mainly small ones) have been partially or completely removed in the twentieth century. Also in Europe, several dams will need to be decommissioned soon (e.g. in the Alps (leNews 2017)). Moreover, the oil & gas industry is currently facing increasingly relevant challenges, according to Parente et al. (2006), the number of petroleum installations in the world exceeds 7,500 units. The US case is dominated by the decommissioning and dismantling of the offshore installations in the Gulf of Mexico (where approximately 4,000 structures used to produce oil and natural gas (Kaiser 2006)) and whose costs are estimated to reach several billion by 2040 (IHS Markit 2017). Europe is not exempt from these concerns and, according to the UK House of Commons (2017), the scale of decommissioning the UK oil & gas Continental Shelf comprises thousands of wells to plug and abandon, as well as hundreds of other subsea platforms and floating installations to decommission. Additionally, discussion dealing with the end-of-life of low carbon infrastructure, such as photovoltaic panels and wind farms has also started to emerge (Cartelle Barros et al. 2017; Topham & McMillan 2017).

Among other decommissioning endeavours, the nuclear industry is the sector with the biggest technical, economic and social-related challenges. Nuclear decommissioning is the final phase in the life-cycle of a nuclear facility and it is a complex, long and expensive process with a multidisciplinary nature (Laraia 2012a). Moreover, not only Nuclear Decommissioning Projects and Programmes (NDPs) are expensive, but also the cost estimate for most of these projects keep increasing and there is a limited understanding of why this happens. For example, the latest figures estimating the decommissioning of the UK nuclear civil legacy currently reach £229billion (NDA 2019), a figure considerably higher than the first estimates published by the NDA referring to 2005 of £24billion (NDA 2006, p.72). Within this legacy, the estimates of Sellafield (i.e. the biggest UK and European nuclear site undergoing decommissioning) currently reach £160billion (NDA 2019), a considerable increase from 2005, when Sellafield NDP estimates were at £14.9billion (NDA 2006, p.72). Because of these high figures, as well as the size and techno-socio-economic effort of Sellafield (hosting around 1,400 buildings, concentrated on a 6 km^2 site, with more than 10,000 employees (NDA 2017; NAO 2015)), Sellafield can be called a "megaproject". However, even without reaching any specific economic threshold, other NDPs could be considered megaprojects, due to their economic size, their complexity, the number of stakeholders that they involve and the fact that they both are shaped and shape the context where they are delivered. Also, other NDPs suffer from poor cost performance, such as Ignalina NDP in Lithuania (European Court of Auditors 2016). Decommissioning projects as highlighted in the next sections, are remarkably under-investigated in the project management literature.

Concerning nuclear decommissioning, the abovementioned limited research could be caused by the fact that the knowledge in building and operating nuclear facilities has been developed over decades, while the number of completed NDPs is extremely small compared to the ones that have been built. For example, looking at NPPs, more than 500 NPPs (the majority of which still in operations (IAEA 2019)), and several other nuclear facilities have been built across the world, but only a negligible number of NPPs (16 NPPs in the whole world (OECD/NEA 2016)) have undergone complete decommissioning. The low number of nuclear facilities that have been completely decommissioned is mostly due to the following reasons:

- Early NPP were designed for a life of 30 years (WNA 2019a), but several factors such poor knowledge management, loss of knowledge, NPPs not designed to be decommissioned, and an early tendency in preferring the deferred dismantling strategy (e.g. in France) caused the postponement of the beginning of decommissioning (Laraia 2012b);
- Newer NPPs have been designed for a life of 40 – 60 years (WNA 2019a), so the majority of the NPPs installed have not reached the end of their forecasted lifecycle yet;
- Some nuclear facilities have benefited from a lengthening of their operating license.

However, nuclear decommissioning is an extremely urgent and growing challenge. For example, in the UK, there are currently 13 sites hosting reactors in permanent shutdown (IAEA 2019) at a different stage of decommissioning, and three more sites will experience reactor shutdown in the next five to ten years (WNA 2019d). Similarly, France, who currently has seven sites hosting reactors in permanent shutdown (IAEA 2019) and derives 75% of its electricity from nuclear energy, has the plan to shut 4-6 reactors in the next decade to comply with Government policy to reduce the electricity from nuclear to 50% (WNA 2019b). Germany has also agreed in 2011 to shut seven reactors by 2022 (WNA 2019c).

Not only are concerns caused by the fact that the number of NDPs in Europe is rapidly growing, but also by a number of other intertwined challenges. These include:

- Technical and regulatory-related challenges, which arise due to the management of radioactive and highly toxic material arising from decommissioning and the high volumes to be lifted and transported (Steiner 2012; Valencia 2012);
- Economic and financial challenges, which arise as decommissioning costs are in the order of billions and keep increasing, while often insufficient or inexistent provisions were reserved for decommissioning and waste management (LaGuardia & Murphy 2012);
- Social and ethical challenges, including the concerns about current and future generations that have to bear the cost of decommissioning (as most of decommissioning in Europe is funded with tax-payers' money), while the benefits provided by the infrastructure were exploited by past generations (Taebi et al. 2012);
- Environmental challenges, which arise in the attempt to restore the site to its previous condition (Fellingham 2012).

In summary, research on NDPs is hindered by the complexity of NDPs, the small sample size of existing NDPs, as well as by the limited number, availability, and reliability of information on these NDPs. Moreover, until now, NDPs have been overlooked by the project management literature. This is discussed in the next section.

A.1.2 The lack of project management research on nuclear decommissioning

Despite the complexity, the techno-socio-economic relevance, and the often poor performance of NDPs, there is very limited project management academic research investigating the NDP characteristics that affect the NDP performance. This is attested for example by the fact that the search in Scopus for the keywords "project management", "success", "factors", and "construction", highlights 738 publication, while the search restricted to "decommissioning" shows only eight results[1]. Moreover, while there is an extensive and growing literature on "megaprojects"

[1] Exact query: "project management" AND "success" AND "factors" AND "decommissioning". The word "decommissioning" was also substituted by "dismantling" (showing only one result) and by "end-of-life" (showing no result).

that focuses on construction (e.g. (Flyvbjerg et al. 2016; Merrow 2011; Ansar et al. 2014)), the search in Scopus for the keywords "decommissioning" and "megaprojects" provided only one result[2]. Referring only to "nuclear decommissioning", the search in Scopus reveals 470 publications (as of at beginning of March 2019), but only two of them have been published in "project management journals"[3].

The search in Scopus based on the presence of keywords either in the title, abstracts, and keywords, fails to highlight relevant practitioner-based publications, in which (often scattered) information about nuclear decommissioning form the project management perspective is available. These publications have recently increased in number and quality, and include reports published 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), the European Commission (EC 2018), the European Court of Auditors reports (2016; 2011) and others (such as (Öko-Institut 2013; Wuppertal Institute 2007)).

However, these above-mentioned publications tend to focus mostly on NDPs cost estimates (e.g.(IAEA/OCED-NEA 2017; OECD/NEA 2012)), discuss costs but not time performance (e.g. (OECD/NEA 2016)), focus on a small number of European NDPs (European Court of Auditors 2016; Öko-Institut 2013), or provide the perspective of single experts on single topics, respectively authors of different chapters of (Laraia 2012b). However, a European-wide study on the NDP characteristics that affect the NDP performance is missing. This research addresses this gap, leveraging on the above-mentioned publications, which consist of the most relevant source of information to understand the research context. In fact, there is a growing urgency to investigate NDPs, caused by the fast-growing number of facilities that are approaching their end-of-life, and the costs that decommissioning is involving and will involve more and more in the future. Therefore, research on how to understand

[2] The exact query in Scopus "decommissioning" AND "megaprojects" showed only one results, i.e. (Invernizzi et al. 2018). The word "decommissioning" was also substituted by "dismantling" and by "end-of-life", both searches showing no results.

[3] Exact query in Scopus: "nuclear decommissioning". The two above-mentioned papers have been published respectively in the "International Journal of Managing Projects in Business" and in the "International Journal of Project Management". Respectively, these papers describe a methodology based on benchmarking to investigate NDPs (Invernizzi et al. 2018), and the social challenges that affect NDPs (Invernizzi et al. 2017b).

the NDP characteristics that affect the NDP performance, to ultimately support the selection, planning, and delivery of NDP with better performance will be more and more important. One way to tackle this challenge is through benchmarking. So, the next sections introduced benchmarking as a way to investigate NDPs.

A.1.3 Benchmarking as a way to investigate NDPs

Benchmarking is one way of investigating NDPs, as it promotes the identification of best practices in order to ultimately improve the project performance.

In the literature, benchmarking has been described through a variety of definitions and a number of steps[4]. For example, Anand & Kodali (2008), reviewed 35 published models and highlighted that there are only 13 common steps of the benchmarking analysis, out of 71 investigated, which highlights how benchmarking needs to be tailored to the specific context in it applied onto. Conversely, Fernandez et al. (2001, p.282) highlighted only five generic steps of benchmarking, while Büyüközkan & Maire (1998, p.104) emphasized a 5-phase/15-steps benchmarking process. Moreover, the focus of benchmarking changed over time, and has evolved from being only product oriented, into being focused on product and on the processes of competitors; then benchmarking developed progressively into looking at companies with strong practices independently from their industrial sector, to then become strategic benchmarking used to trigger fundamental company change (Barber 2004, p.303-304). In this research, the author relies mostly on Anand & Kodali (2008), El-Mashaleh et al. (2007), Costa et al. (2006), Garnett & Pickrell (2000), who emphasise the importance of project comparison in order to identify good practices to stimulate the formulations of ideas for the project's improvement (i.e. revolving around the same definition provided by the Project Management Body of Knowledge (PMBOK 2013)).

The context of nuclear decommissioning is one of a relatively "young" industry. This means that the number of completed and ongoing NDPs is still very low, the existing information is limited, the available information is scattered and often comes in a range of different formats, with a different level of details and quality. Hence, the

[4] The selected literature about benchmarking is presented in the appendix of Publication I.

investigation of NDPs based on benchmarking needs to take into account these limitations. Indeed, while benchmarking has been traditionally used in the construction industry, in order to measure the company performance and identify areas of improvement (e.g. (Yeung et al. 2013; El-Mashaleh et al. 2007)), and it often relies on large data sets (El-Mashaleh et al. 2007; Love & Smith 2004), the context of decommissioning hinders the direct application of benchmarking (as performed in the abovementioned publications) on NDPs. In other words, the context of nuclear decommissioning calls for the development of a methodology based on benchmarking that is suitable to identify ideas for improvement through project comparison, even if the sample size of these projects in small. This brings the focus of this research to the firsts of the "common steps" of benchmarking identified by (Anand and Kodali 2008, p.279), i.e. the systematic identification of "what" and "how" to analyse, before any actual change can be implemented in an NDP, and the impact of this change can be measured. In this research, the "what" are European NDPs, intended as site-level endeavours, while the "how" refers to the methodology developed to investigate NDPs. The next section elaborates on the definition of the research aim and objectives, which were triggered by the abovementioned considerations.

A.2 Research aim and research objectives

From the preliminary literature review (briefly introduced in section A.1, and expanded to perform the research presented in each of the publications of section B), and from scoping interviews with decommissioning practitioners, it emerged:

- The complexity and urgency of investigating the nuclear decommissioning industry;
- The limited sample size of existing NDPs;
- The limited number, availability, and reliability of the information on these NDPs;
- The dearth of academic literature investigating the NDP characteristics that affect the NDP performance from the project management perspective;
- The potential that benchmarking has in addressing this gap, but the impracticability of applying benchmarking directly on NDP, which leads to the need to develop a methodology based on benchmarking.

From these considerations, the author derived the aim of this research. The aim of this research is to develop and apply a methodology based on benchmarking to investigate the NDP characteristics that affect the NDP performance.

In this industry-funded research, the unit of analysis is NDPs, intended as site-level endeavours as defined in the PRIS-IAEA (IAEA 2019). NDPs are selected among European ones due to the remarkable differences (e.g. in terms of regulatory-context) with other NDPs (e.g. in the US or Japan) and the proximity of the researcher to these NDPs. Moreover, NDPs are only selected among commercial ones (i.e. military or research reactors are excluded from this research), due to the industry interest and because of the number of public information available on NDP compared to other decommissioning projects.

To achieve the abovementioned aim, the author developed four "primary objectives" (I to IV) and two "secondary objectives" (V.a and V.b), which derive from the primary ones. These objectives read as follows:

I. Develop a methodology based on benchmarking to improve learning across projects and investigate the project characteristics that affect the project performance. This objective has been achieved through the research presented in Publication I.

II. Apply part of this methodology to investigate the social-related challenges of NDPs. This objective has been achieved through the research presented in Publication II.

III. Apply part of this methodology and collect and analyse the NDP characteristics that affect the NDP cost and time performance. This objective has been achieved through the research presented in Publication III.

IV. Apply part of this methodology and present a systematic approach to statistically test the association between the NDP characteristics and the NDP cost performance. This objective has been achieved through the research presented in Publication IV.

V. Identify and analyse two NDP characteristics in depth. These NDP characteristics emerged from the research performed to reach the "primary objectives". The derivation of the two research objectives, i.e. objective V.a and V.b (respectively related to the two selected NDP characteristics selected to be investigated in depth) is explained in section A.3, i.e. the "research development" section.

In summary:

- Objective I refers to the development of a methodology based on benchmarking suitable to investigate NDPs;
- Objective II, III and IV are related to the application of this methodology;
- Objectives V.a and V.b are "secondary objectives" that embrace the in-depth investigation of two NDP characteristics that emerged during the development of this overall research.

The next section, section A.3, describes the research development, introducing the research questions that each piece of research addresses in order to achieve each research objective, and in this way contributing towards the achievement of the overall research aim.

A.3 Research development

This industry-funded research started with a preliminary literature review of project management aspects of nuclear decommissioning and benchmarking, in order to gain a broad understanding of both the research field and the possible approaches for benchmarking NDPs. From this early review, it emerged that despite the challenges associated with decommissioning, the effort that NDPs require, and the limited current knowledge about managing NDPs, the majority of academic publications on decommissioning took the “hard science” perspective, for example, investigating chemical, physical, radiological aspects of NDPs. Conversely, the aspects related to project management (in general) and how to benchmark NDPs (more specifically) in order to investigate the NDP characteristics that affect the NDP performance, was largely disregarded.

NDPs include a number of different types of projects, such as the decommissioning of civil nuclear power plants, military facilities, and research reactors that, at the end of their operational life need to be decommissioned. Thus, the number, availability, and reliability of data and information on these NDPs (as well as their cost) are extremely various and diverse. From the preliminary literature review, it also emerged that there are hardly any NDPs that have been recently completed (OECD/NEA 2016). One NDP that has been completed, in 2005, under budget and within the schedule, and upon which official documents are available is the case of Rocky Flats NDP in the US.

Rocky Flats was a nuclear weapons production facility that produced plutonium and enriched uranium from 1953 until 1989. It was owned by the US Department of Energy (DOE) and was managed by a series of weapons contractors (DOE 2013; Cameron & Lavine 2006). In 1989, the FBI raided the Rocky Flats because of suspicion that unreported pollution might be occurring, and in 1992, the Rocky Flats nuclear program was permanently withdrawn. In 1995, the DOE estimated that the clean-up and the closure of the facility would require more than 70 years and $36 billion. However, in the same year, a joint venture won the contract claiming that they could close the project by 2006 for $3.96 billion. In October 2005, 800 buildings had been demolished, all radioactive waste had been removed and soil and water had been remediated, with a final cost of less than £3.5 billion and 14 months in advance on the 2000 estimates (Bodey 2006), with remediation pollution levels, which surpassed initial federal standards (Cameron & Lavine 2006). The review of this case trigged the cross-comparison between Rocky Flats NDP and Sellafield NDP, i.e. the biggest and most challenging NDP in the UK. Indeed, as introduced in section A.1, Sellafield site hosts around 1,400 buildings, of which 240 are nuclear facilities, and its decommissioning plan involves a series of activities that range from reprocessing spent fuel from old nuclear reactors both from the UK and abroad, retrieving, packaging and transporting waste from existing storage facilities, demolishing the buildings, and clearing the final site (NAO 2018; NAO 2015). Sellafield's decommissioning estimates reach more than £160 billion, in an endeavour that is expected to last for more than 120 years (NDA 2019), figures with an order of magnitude comparable to the original DOE estimates for Rocky Flats NDP. Therefore, an early detailed cross-comparison between these two NDPs was valuable to gain knowledge of the nuclear decommissioning field, and start to both validate and complement the findings from the preliminary literature review concerning the NDP characteristics that affect the NDP performance. This cross-comparison between Rocky Flats and Sellafield is summarized in Publication [a], in the appendix.

Publication [a] was presented in ICONE2016 (a leading nuclear conference, indexed in Scopus), and was discussed in other industry-related national and international meeting and conferences. This cross-comparison supported the framing of the subsequent piece of research (see Figure 1). Indeed, Publication [a] informed the following pieces of research both from the methodological perspective (as it emphasized the value of cross-comparing NDP at a site level) and because it both validated and complemented the findings from the early literature with the NDP characteristics that were relevant for the successful completion of Rocky Flats NDP.

In parallel to acquiring knowledge on decommissioning, the author continued with the literature review on benchmarking. This review highlighted the limited agreement in the definition of benchmarking and of the steps to perform a benchmarking analysis, as well as a wide-spread application of benchmarking based on large number of completed project (which is not the case of NDPs) or based on private company data (to which the author did not have access). Hence, the first research objective, reads as follows:

Objective I: to develop a methodology based on benchmarking to improve learning across projects and investigate the project characteristics that affect the project performance.

This objective was achieved through the research presented in Publication I. Publication I develops a methodology based on benchmarking to improve learning across projects and investigate the project characteristics that affect the project performance. Publication I is based on a review of studies discussing and applying benchmarking, and suggests to combine a more qualitative cross-comparison of several NDPs (e.g. such as the one between Rocky Flats and Sellafield) with a more quantitative analysis (e.g. statistical tests). Both qualitative and quantitative analyses are hindered by the limited number, availability, and reliability of existing data and information on NDPs, but can complement each other providing valuable insight.

Drawing from the preliminary literature review, the findings of the cross-comparison presented in Publication [a], scoping interviews, as well as considering the number, availability, and reliability of existing data and information on NDPs, the application of the qualitative cross-comparison (envisaged in the methodology presented in Publication I) focused firstly on the social-related challenges of NDPs. Objective II reads as follows:

Objective II: to investigate the social-related challenges of NDPs as site-level endeavours.

Objective II is achieved by addressing the two research questions below:

Research questions [Objective II]:

- Which are the main social challenges that arise during the development of a NDP, and how do they affect NDPs?
- Which are the best practices to socially and ethically manage these challenges, and successfully meet the scope of the project?

The research presented in Publication II deals with objective II. In Publication II, the social challenges that arise during the development of an NDP were analysed, together with their impact. Moreover, guidelines on how to address NDP social challenges were proposed.

The application of the more qualitative part of the methodology presented in Publication I focused on the NDP time and cost performance. However, unlike the research presented in Publication II, this piece of research was based mostly on primary data and information (see Figure 1). Objective III read as follows:

Objective III: collect and analyse the characteristics of NDPs that affect the NDP cost and time performance.

Objective III is achieved by addressing the research question below:

Research questions [Objective III]: Which NDP characteristics affect the difference between time and cost estimates of NDPs and the NDPs' actual time and costs?

The author uses the terms "characteristics" and "performance" in place of the more common "success factors" and "success criteria" used to measure the "project success", due to:

- the exploratory nature of this research, which is a first step towards a better understanding of what drives (but also what hinders) the NDP performance;
- the fact that the author wants to give neither a positive nor a negative connotation to a list of characteristics that affect the project performance (as NDP characteristics such as the location of the NDP or the contractual agreement could have a positive, negative or neutral effect on the NDP performance);
- the complexity of defining what is a "successful decommissioning project", e.g. at which point in time "success" should be evaluated, according to which stakeholders, etc. (see (Turner & Zolin 2012; Davis 2014));

The research presented in Publication III deals with objective III, where information collected from semi-structured interviews with experienced decommissioning practitioners were analysed through content analysis.

The research conducted to achieve objective III, and in particular, the collection and codification of the NDP characteristics allowed the creation of a database (of around 1,900 cells) of NDP characteristics through which each NDP was described. So, informed by the methodology of Publication I, and based on the database of

NDP characteristics created while progressing with the research presented in Publication III, objective IV could be achieved. Objective IV reads as follows:

Objective IV: to present a systematic approach to test the association between the NDP characteristics and the NDP performance through statistics.

Objective IV is achieved by addressing the (implicit) research question below:

Research question [Objective IV]:

- How can the relationship between NDP characteristics and NDP performance be assessed through statistics?

The research presented in Publication IV deals with objective IV, where two statistical tests were selected and described, and their application on 24 NDPs was performed, with an illustrative purpose. The literature suggests many criteria to assess the project performance. Among the possible criteria to assess the NDP performance, Publication IV focuses on the (loosely called) NDP cost overruns, due to the extremely limited number, availability and reliability of comparable data of other NDP performance indicators (indeed, there is an almost complete absence of information about the duration of NDPs, its changes in time, and the definition of other performance indicators vary considerably from country to country). The calculation of cost overruns for the research presented in Publication IV triggered thoughts surrounding the meaning of "cost overruns" and how cost overruns should be calculated. Publication [b] in the appendix of this thesis focuses on this topic.

Additionally, the author investigated in depth some specific NDP characteristics. Unlike the "primary objectives" I, II, III and IV, objectives V.a and V.b are "secondary objectives" as they have been delineated at a later stage of development of this PhD research. These objectives both draw from early scoping interviews, the empirical findings from the piece of research performed to address the "primary objectives", and take advantage of the opportunities that the researcher was confronted with. Indeed, objective V.a and V.b stemmed from a combination of: (i) the researcher and industry interest in investigating the relevance of "scope changes" and the topic of "value" in decommissioning; (ii) from the opportunities that emerged during the PhD progress (e.g. the possibility to work in a company in the nuclear decommissioning industry and develop the research performed to address objective V.a); and (iii) thanks to the researcher's growing network (which allowed to contact a number of relevant interviewees for the data collection and collaborate with academic colleagues experts of the topic in order to address objective V.b).

Objective V.a reads as follows:

Objective V.a: to analyse the communication about scope changes in nuclear decommissioning, showing the importance of monitoring and addressing 'weak signals' (e.g. frustration)

Objective V.a is achieved by addressing the two research questions below:

Research questions [Objective V.a]:

- To what extent should and could weak signals of stakeholders' discomfort be used to highlight operational inefficiencies on the information flow associated with high transaction costs?
- How can communication and information management be improved to address the stakeholders' discomfort, optimise the information flow and ultimately increase the overall project performance?

The research presented in Publication V deals with objective V.a, and highlights that the communication about scope changes of a major project to be delivered by a project-based company to its long-term client (i.e. Sellafield NDP) could be considerably improved, ultimately contributing to improving the performance of the NDP performance itself.

Objective V.b reads as follows:

Objective V.b: to explore the potential role of VM in nuclear decommissioning.

Objective V.b is achieved by addressing the research questions below:

Research question [Objective V.b]:

- What does "value" mean in the context of decommissioning?

- What are the constraints that affect decommissioning projects that can be addressed with VM?
- What are the requirements for a successful implementation of VM in decommissioning projects?

The research presented in Publication VI deals with objective V.b. This research stems from the desire to increase the understanding of how to improve the application of VM in decommissioning to ultimately deliver NDPs with better performance, and it is based both on a review of the literature of VM in construction projects, as well as semi-structured interviews with decommissioning practitioners (as described in Publication VI).

Figure 1 below summarizes the research development and highlights how the different piece of research are strongly interlinked. The publications in the main body of this thesis are highlighted in bold and lay in thick-line boxes [I to VI]. The publications in the appendix are in dotted-line boxes (Publication [a] and [b]). The double-line arrows on the bottom-left side of the graph illustrate how the methodological approach informed the subsequent piece of research. The single-line arrows on the top-right of the graph illustrate how results informed the subsequent piece of research. The shaded area highlights the "primary objectives" dealt by Publications I, II, III and IV, while objective V.a and V.b are the "secondary objectives", which are dealt by Publication V and VI.

The research developed in each publication in section B of this thesis contributes to achieving the overall aim of this research. Each individual publication provided new insights and ideas that were used as pre-understanding for the subsequent one(s). Moreover, each publication drew from the previous ones, benefitted from the feedback received both during the review process and after the publication of the research, and informed the following publication(s) through either its methodological approach, the research findings or both.

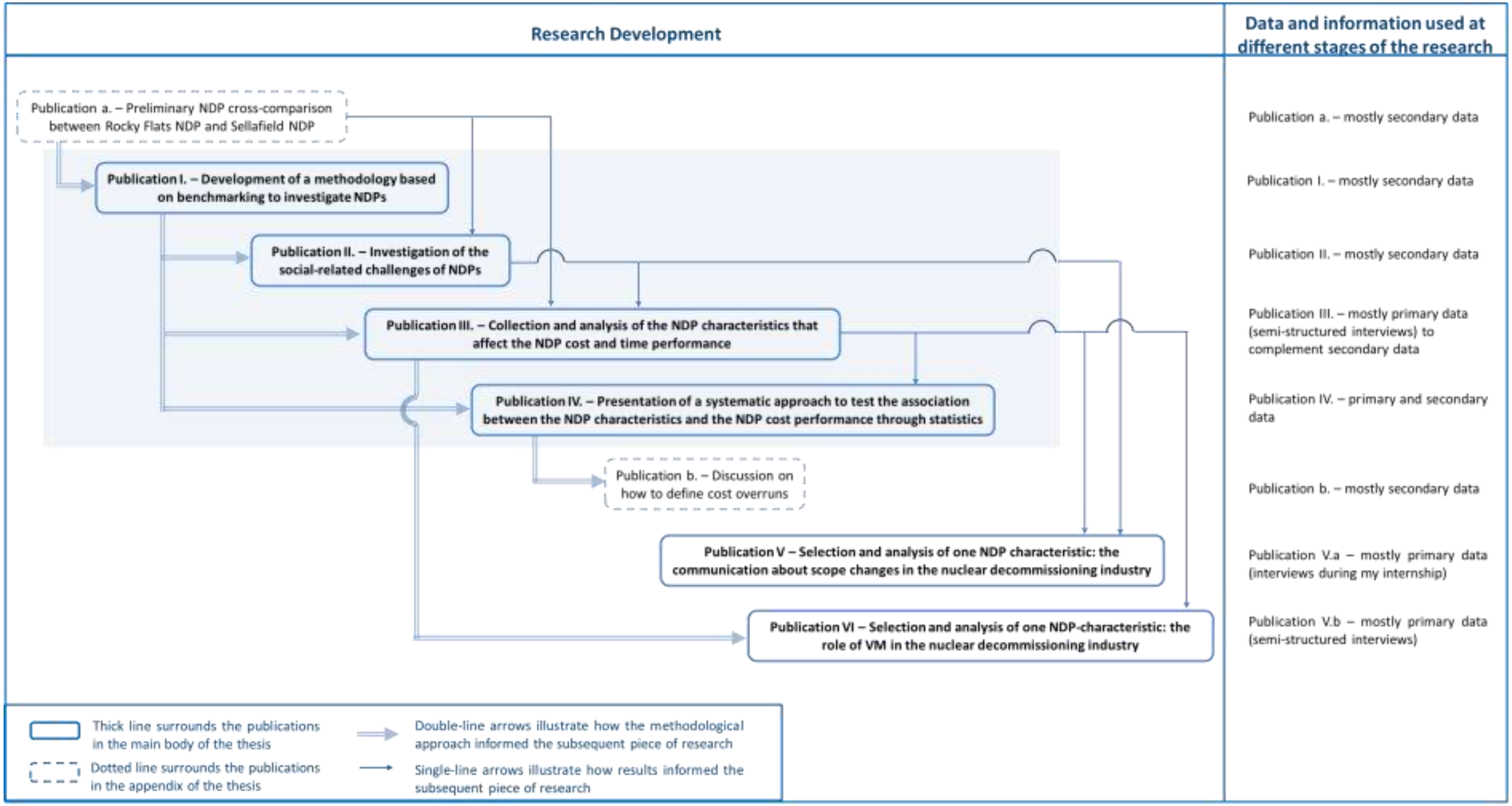

Figure 1. Graphical representation of the research development

A.4 Research design

Research designs need to be tailored to answer the research questions. This PhD research encompasses a series of research questions. Hence, the detailed designs crafted to answer each research questions is described in each of the publications in section B. The aim of this section is to describe the overall research philosophy. The book “Research Methods for Business Students” (Saunders et al. 2009) is the main reference that has been used to develop the framework of this research. Additionally, the book “Business research methods” (Bryman & Bell 2007) and “Doing business research: a guide to theory and practice” (Lee & Lings 2008) have been reviewed and used to complement (Saunders et al. 2009).

A.4.1 Research philosophy and approach

The term “research philosophy” refers to the development of knowledge and the nature of that knowledge. In this PhD research, pragmatism (sometimes referred to as the “pragmatic approach” (Morgan 2007, p.49)) has been adopted since pragmatism places the research problem in a central position and promotes several approaches to deal with the problem. For pragmatists, methods need to match the specific questions and purpose of the research (Mackenzie & Knipe 2006).

The research ontology, which is “*concerned with nature of reality*” (Saunders et al. 2009, p.110) and represents “*the researcher’s view of the nature of reality or being*” (Saunders et al. 2009, p.119), is for pragmatists primarily driven by the quest to better answer the research questions. Saunders *et al.* (2009) identify two aspects of ontology, i.e. the objectivist view and the subjectivist view. Researchers with an objectivist view believe that entities exist in reality, externally and independent from social actors. Researchers with a subjectivist view believe that social phenomena are created from the perceptions and actions of social actors, and are in a constant state of revision. As understood while reviewing the literature on NDPs, it emerged that NDPs present both strictly-technical, as well as social and organizational challenges. In particular: the collection of primary data and information about the NDP characteristics and their relationship with the NDP performance derives from the perspective and standpoint of experienced interviewees, which requires a more subjectivist view (as in Publication III), while the performance of NDP are assessed independently from the interviewees’ perspectives and standpoint, and this requires a more objectivist view (as in Publication IV). Therefore, the author argues that the investigation of the NDP characteristics and NDP performance requires the adoption of an overall mixed ontological perspective, which combines subjectivism and objectivism. In terms of the researcher's view on what constitutes acceptable knowledge in a field of study, i.e. the research epistemology, both "*observable phenomena and subjecting meanings*", that are typical of pragmatism (Saunders et al. 2009, p.119), are suitable to increase the knowledge in the context of NDPs.

Regarding the choice of the most suitable research approach, the author leans towards a more inductive approach, as the inductive researcher is particularly concerned with the research contexts when gathering data and information, and is able to formulate new theories as a result of the analysis of these data and information. Moreover, researchers are this tradition are likely to work with both qualitative and quantitative data and use a variety of methods to collect information. However, between the deductive and the inductive approach there is no competition, "*but rather an essential continuity and inseparability between inductive and deductive approaches to theory development*" (Parkhe 1993). Therefore, some deductive-inductive iterations occurred.

A.4.2 Research strategy

As introduced in section A.2, this research is affected by numerous challenges and it is facilitated by other aspects which both contributed to shaping the research design of the PhD. On the one hand, the research challenges derive mostly from the complex nature of the nuclear industry, the small sample of existing NDPs, the limited number, availability, and reliability of the information, and from the limited academic research on NDPs performed until now in the area of project management. Moreover, the number of nuclear decommissioning practitioners with also managerial expertise is (although growing) still low.

On the other hand, this research can benefit from reports from international organizations (such as the International Atomic Energy Agency and the OECD/Nuclear Energy Agency), which have been recently promoting greater national and international transparency, as well as from the fact the UK industry is receptive and willing to be involved with academic projects. Hence, the researcher could benefit from the possibility to get in contact with the nuclear decommissioning practitioners with managerial expertise both in the UK and abroad, thanks to the support of her industrial supervisor(s), by participating and presenting to international conferences and meetings and being involved in international projects (see section D.2).

Considering both the shortcomings (e.g. the availability of information) and the advantages that this research could benefit from (e.g. the possibility for the researcher to work in a company), each publication in section B describes the research design elaborated to answer its specific research questions. This decision is in line with the pragmatist belief that the research problem has a central position and that methods need to match the specific purpose of the research.

In terms of data collection and analysis, both primary and secondary data and information have been collected and analysed depending on the availability of information, and the stage of the research. Figure 1 in section A.3 summarizes the main type of input data per each publication, while each publication in section B described more in detail the process of data collection and analysis.

B. Publications

Publication I :

Invernizzi, D.C., Locatelli, G. & Brookes, N.J., 2018. A methodology based on benchmarking to learn across megaprojects: the case of nuclear decommissioning. *International Journal of Managing Projects in Business*, 11(1), pp.1–18.

Publication II:

Invernizzi, D.C., Locatelli, G. & Brookes, N.J., 2017. Managing social challenges in the nuclear decommissioning industry: A responsible approach towards better performance. *International Journal of Project Management*, 35(7), pp.1350–1364.

Publication III:

Invernizzi, D.C., Locatelli, G. & Brookes, N.J., 2018. Characterising nuclear decommissioning projects: An exploration of the end-of-life of nuclear infrastructure – Submitted to *Construction Management and Economics*

Publication IV:

Invernizzi, D.C., Locatelli, G. & Brookes, N.J., 2019. An exploration of the relationship between nuclear decommissioning projects characteristics and cost performance. *Progress in Nuclear Energy*, 110, pp.129–141.

Publication V:

Invernizzi, D.C., Locatelli, G. & Brookes, N.J., 2018. The need to improve communication about scope changes: frustration as an indicator of operational inefficiencies. *Production Planning and Control*, (May), pp.1–14.

Publication VI:

Invernizzi, D.C., Locatelli, G., Grönqvist, M. & Brookes, N.J.2019. Applying value management when it seems that there is no value to be managed: the case of nuclear decommissioning – Published online in *International Journal of Project Management*, and available online since the 28th January 2019

Publication I

“A methodology based on benchmarking to learn across megaprojects: the case of nuclear decommissioning”

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A methodology based on benchmarking to learn across megaprojects

The case of nuclear decommissioning

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Abstract

Purpose – The literature lacks a single and universally accepted definition of major and megaprojects: usually, these projects are described as projects with a budget above $1 billion and a high level of innovation, complexity, and uniqueness both in terms of physical infrastructure and stakeholder network. Moreover, they often provide fewer benefits than what were originally expected and are affected by delays and cost overruns. Despite this techno-economic magnitude, it is still extremely hard to gather lessons learned from these projects in a systematic way. The purpose of this paper is to present an innovative methodology based on benchmarking to investigate good and bad practices and learn from a portfolio of unique megaprojects.

Design/methodology/approach – The methodology combines quantitative and qualitative cross-comparison of case studies and statistical analysis into an iterative process.

Findings – Indeed, benchmarking offers significant potential to identify good and bad practices and improve the performance of project selection, planning, and delivery.

Research limitations/implications – The methodology is exemplified in this paper using the case of Nuclear Decommissioning Projects and Programmes (NDPs).

Originality/value – Indeed, due to their characteristics, NDPs can be addressed as megaprojects, and are a relevant example for the application of the methodology presented here that collects and investigates the characteristics that mostly impact the performance of (mega)projects, through a continuous learning process.

Keywords Benchmarking, Methodology, Megaprojects, Cross-case study, Nuclear decommissioning

Paper type Research paper

1. Introduction

Major and megaprojects are often defined as projects with a budget above $1 billion with an high level of innovation and complexity (Flyvbjerg *et al.*, 2003; Van Wee, 2007; Merrow, 2011; Locatelli, Mariani *et al.*, 2017). However, already in the mid-1980s, Warrack (1985) argued that $1 billion is not a constraint in defining megaprojects, since sometimes a relative approach is needed. In fact, in some contexts, a much smaller project (such as one with a $100 million budget), could constitute a megaproject. Similarly, Hu *et al.* (2013) claim that a deterministic cost threshold is not appropriate for all countries, and a relative threshold such as the GDP should be used instead.

Even without defining a single threshold, megaprojects share the characteristics of not only being extremely expensive and long, but also politically sensitive, since they are often commissioned (at least partially) by the governments and involve a large number of external and internal stakeholders. Moreover, these projects are both influenced by the context in which they are delivered and they are able to influence the context themselves (Merrow, 2011). Additionally, due to the size and complexity of both their physical infrastructure and stakeholder network, it is still extremely hard to gather and investigate lessons learned from these projects in a systematic way.

Due to this techno-economic, political, and social magnitude, megaprojects have risen significant interest not only among practitioners, but also among academics. Nevertheless,

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due to their uniqueness, it is still extremely hard to gather good and bad practices and develop empirically based guidelines in a systematic way.

This paper addresses this challenge, presenting a methodology to improve learning across projects and ultimately investigates the project characteristics (i.e. the independent variables) that impact most on the project performance (i.e. the dependent variable).

This methodology is based on benchmarking. Benchmarking refers to the process of comparing projects and, as explained in Section 2, it offers significant potential to investigate the characteristics that impact most on the project performance. This methodology is applied to Nuclear Decommissioning Projects and Programmes (NDPs), as NDPs are extremely complex, long, and expensive, with a budget that often exceeds $1 billion; they are politically sensitive and involve a large number of external and internal stakeholders (LaGuardia and Murphy, 2012; Invernizzi *et al.*, 2017c). Therefore, NDPs can be addressed as megaprojects.

Nevertheless, this methodology can be adapted to all major and megaprojects where the uniqueness of projects and the low number of cases available hinder the use of analysis based on big numbers.

The rest of the paper is organized as follows. Section 2 critically reviews recent research on benchmarking and compares benchmarking studies applied on the construction industry. Section 3 stems from the literature and proposes a methodology to adapt the benchmarking approach to the situation where the number of cases is low and the information available is scattered. Then, this methodology is exemplified using the case of NDPs in Section 4. Section 5 is dedicated to discussion and conclusions.

2. Benchmarking analysis in the literature

The meaning of the term "benchmarking" has been widely discussed in the last decades and, as shown in Table AI, there are different definitions of "benchmarking" and of the benchmarking "steps and/or phases" in the literature. Already in 1992, benchmarking had been described through 49 definitions (Anand and Kodali, 2008, quoting (Spendolini, 1992)) and through a different number of steps and phases. More recently, Anand and Kodali (2008) reviewed 35 published models and highlighted that there are only 13 common steps of the benchmarking analysis, out of 71 investigated. Therefore, before performing a "benchmarking analysis," it is fundamental to agree on its definition. In this research, the authors follow the PMBOK (2013, p. 116) definition, where 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." Garnett and Pickrell (2000, p. 57) 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." Ramirez *et al.* (2004) also state that it is necessary to complement a quantitative benchmarking system with a qualitative-based one, in order to establish causal relationships. This demonstrates the need to adapt benchmarking case by case. Within the construction industry, benchmarking has already been used to compare projects in order to identify successful projects and the reasons for their success, and the interest in benchmarking is significantly increasing because, through finding examples of superior performance, firms can adjust their policies and practices to improve their own performance (El-Mashaleh *et al.*, 2007; Costa *et al.*, 2006; Ramirez *et al.*, 2004). Table AII compares benchmarking analysis applied to the construction industry, highlighting, each study, the aim of the research, the method or model described or adopted, the steps of the analysis and highlights, and the data collection and the number of case studies investigated.

Concerning benchmarking applied to the construction industry (Table AII), the following conclusions can be drawn:

- Benchmarking analysis is suitable to determine the performance of a company, using input metrics (e.g. safety expenses and management expenses) and output metrics (e.g. cost performance, schedule adherence, customer satisfaction, safety performance, and profit) (El-Mashaleh *et al.*, 2007).
- "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), but there is a need to upgrade existing benchmarking initiatives and devise new ones.
- Qualitative benchmarking can enable the comparison 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 program (Ramirez *et al.*, 2004).
- The benchmarking process is as important as the benchmarks themselves (Garnett and Pickrell, 2000), therefore the selection of cases is pivotal.

In conclusion, the benchmarking analysis is recognized to be a valuable tool to improve the performance of projects delivered in different industrial sectors and in different countries. However, the aforementioned analyses are not directly applicable when the number of projects is low and/or the information available scattered (e.g. construction megaprojects and decommissioning megaprojects), and where a single and globally recognized benchmark is missing. Therefore, a new framework needs to be developed to deal with the complexity and low number of major and megaprojects. Table I compares a few techniques for benchmarking and highlights those that are suitable for megaprojects. Section 3 explains this framework, which is exemplified in Section 4 using NDPs. Other statistical analysis, such a qualitative comparative analysis (Schneider and Wagemann, 2012), will be considered at a later stage of the research.

3. The methodology to learn across megaprojects

The methodology presented in this paper is based on the seminal work by Kathleen Eisenhardt (1989), who recommends data collection using multiple methods, introduces the concept of "theoretical saturation," and promotes the deep analysis both of single cases and across cases to develop theories. In particular, the cross-case comparison is an iterative process, where the first step refines the initial hypothesis, the second step verifies the relationships among hypothesis and empirical evidence, and the third step critically compares new theories with existing ones. The case method is described by several authors (e.g. Yin, 2009) and is of significant importance for the current research, even if sometimes criticized due to its limited rigor (Easterby-Smith *et al.*, 2012).

The methodology developed for this research is largely based on empirical evidence, and employs an "inductive" method (rather than a "deductive" one) where "induction" is defined as follows (Gill and Johnson, 2002; Brookes *et al.*, 2015, p. 6): "the induction of particular inferences from particular instances or the development of a theory from the observation of empirical reality." Figure 1 shows the research framework that has been developed by the authors to ultimately collect good and bad practices, and investigate what drives the project performance.

The first step embraces a preliminary literature review and the collection of case studies. This is complemented by semi-structured interviews and site visits. Case studies are selected according to their relevance, their completeness, and the availability of information. The date when these projects have been delivered is also significant, so the rule

Reference, aim of the paper and data collection	Method, model or analysis implemented	Applicable for benchmarking megaprojects?
"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 megaprojects. However, it is not suitable to calculate the median, due to the low number of projects
	(2) Correlation analysis, used to investigate the intensity of the linear relationship between two variables, X_i and X_j. 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 megaprojects
	(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 megaprojects
	(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 megaprojects
	(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 *et al*., 2007) This research presents a benchmarking model that uses input metrics to determine the company performance. Data were collected from 74 construction firms through a survey	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 megaprojects and the information available is too low to implement the DEA
"Power plants as megaprojects: Using empirics to shape policy, planning, and construction management" (Brookes and 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, Invernizzi, *et al*., 2017) 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 megaprojects. 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 megaprojects.

Source: Invernizzi *et al*. (2017)

Table I.
Techniques for benchmarking

"the newer the better" applies. The output of the first step is the preliminary collection of the projects' characteristics that impact on the projects' performance, the selection of case studies, and of the techniques for the data analysis.

The second step consists of the data codification. Indeed, the selected case studies need to be recorded in a standard template. This template could contain several pieces of information grouped into macro-categories, such as:

- an overview of the project, its physical characteristics, and its final end state;
- governance, funding, and contacting schemes; and
- stakeholders and stakeholders' engagement.

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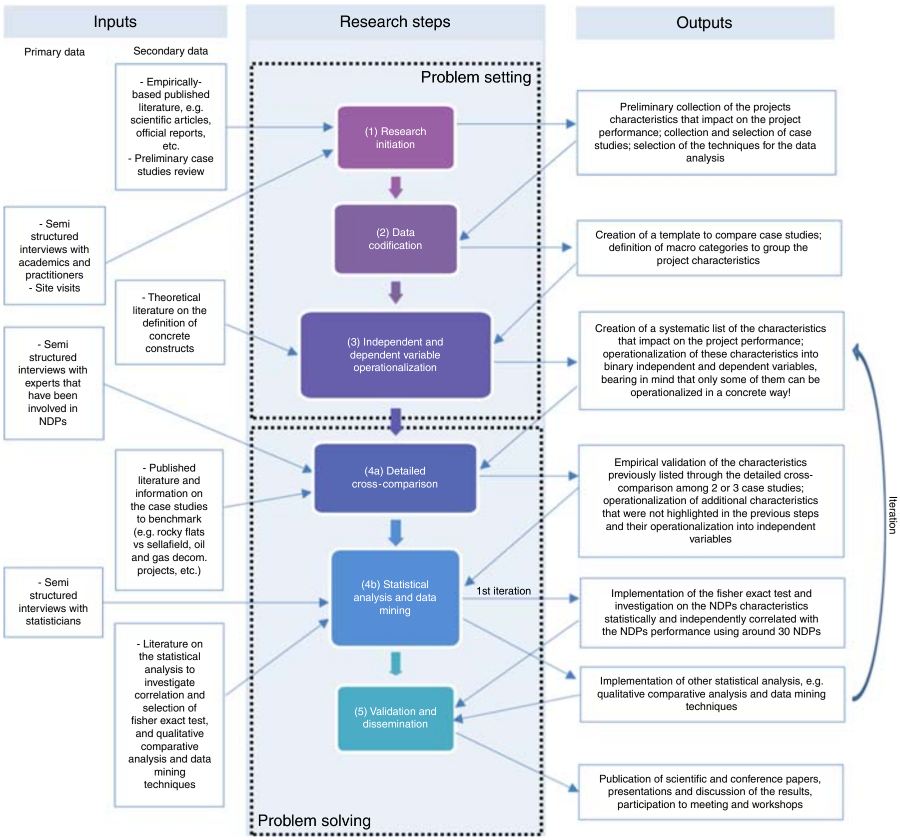
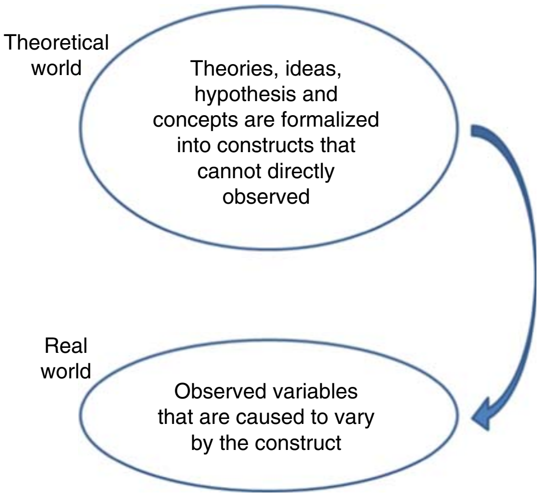


Figure 1.
The five-step methodology

The output of the second step is the development and population of a standard template to allow an easier comparison of projects. From this template, lessons learned can been listed and analyzed.

The third step consists of the operationalization of the independent and dependent variables, i.e., respectively, the project characteristics and their performance (e.g. assessed in terms of cost overruns, Invernizzi *et al.*, 2017a). To do this, it is necessary to differentiate between "concepts" and "constructs," where a construct is a more formalized definition of a concept, a concept being a "general idea in our heads about a variable which has a part to play in our theories" but that still cannot be observed directly (Lee and Lings, 2008). The measurement of a construct is "the process of moving our theoretical constructs into the real world" […], therefore "once we work out exactly how we can represent our constructs in the real world, we have what can been called an operational definition" […]. So, the operational definition outlines exactly "what in the real word we say represents our theoretical constructs" (Lee and Lings, 2008, p. 161) and implicitly means that operational definitions and constructs are not the same thing, as shown in Figure 2. Constructs can describe the world, which is qualitative, quantitative, complex, and dynamic. However, they are not directly observable, therefore observable measures have to be used instead.

Rossiter (2002) adopts the definition of Edwards and Bagozzi (2000) that describes constructs as phenomena "of theoretical interest" and suggests describing them in terms of



Source: Adapted from Lee and Lings (2008)

Figure 2. Theoretical world and real world

the object, including its constituents or components, the attribute, including its components, and the rater entity, where:

(1) the object part of the construct can be singular, collective, or have multiple components, and can be concrete or abstract;

(2) the attribute in the construct is the dimension on which the object is being judged, and can be concrete singular, abstract formed, and abstract eliciting; and

(3) the rater can be an individual, expert, or a group.

The output of the third step is the creation of a systematic list of the characteristics that impact on the project performance and their operationalization into binary independent and dependent variables, bearing in mind that, due to their nature, only some of them can be operationalized in a concrete way. The fourth step consists of the actual data analysis and it is split into two stages, i.e. the qualitative and quantitative cross-comparison and the statistical analysis and data mining, respectively, 4a and 4b in Figure 1.

The qualitative and quantitative cross-comparison of step 4a highlights the good practices that empirically resulted to be relevant for the successful performance of a project. The correlation[1] of these practices, together with "lessons learned" gathered from published literature (e.g. journal articles, official reports, and case studies), semi-structured interviews with experts, and site visits is then investigated in step 4b. Step 4b consists of the statistical analysis. The statistical analysis needs to address: the low number of cases and their complexity, in other words, their (alleged) uniqueness. This is why the Fisher exact test is implemented first. Indeed, 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 (e.g. a project characteristic) is associated with the presence (or absence) of a dependent variable (e.g. the project performance), 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" is, the better. Key features, limitations, and the implementation of the Fisher exact test applied to large construction projects can be found in Brookes and Locatelli (2015), Locatelli *et al.* (2017), and Locatelli, Mikic *et al.* (2017).

Regarding the value of the *p*-value, 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 the actual causation between project characteristics and their performance requires further investigation and validation, e.g. through pilot projects and interviews with experts.

The fifth step is the validation and dissemination of the results.

4. Example of results from the cross-comparison and the statistical analysis

NDPs are complex and affected by high uncertainties, can be characterized by activities that reach national multibillion projects, involve large numbers of partners and stakeholders, and are often (at least partially) commissioned by governments. Therefore, this paper addresses NDPs as megaprojects and uses NDPs to illustrate the methodology described in Section 3. Sections 4.1 and 4.2 illustrate early results from the cross-comparison, while Section 4.3 exemplifies preliminary findings regarding the statistical analysis.

4.1 Cross-comparison between two "similar but different" NDPs

The cross-comparison of NDPs assists the collection of relevant good (and bad) practices, and therefore is envisaged to be performed both within the UK and against other countries (Table II).

Some of the lessons learned from the comparison of two "similar but different" NDPs (Rocky Flats (USA) and Sellafield (UK)) are highlighted below. Lessons learned from ten Oil & Gas decommissioning projects are also collected and summarized in Section 4.2.

Rocky Flats (USA) and Sellafield (UK) are compared because these two NDPs (Invernizzi *et al.*, 2017d):

- are recent NDPs;
- 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);
- have a comparable size; and
- had a decommissioning budget in the order of tens of billions of dollar.

Moreover, there is publically available information in English regarding both these NDPs.

Rocky Flats was a military nuclear weapons facility in Colorado that produced plutonium and enriched uranium from 1953, and stopped operations in 1989. It was owned by the US Department of Energy (DOE) and was managed by a series of weapons contractors. When Rocky Flats was shut down in 1989, due to the significant radioactivity on site, the US DOE estimated that it would have taken 70 years and $36 billion to decommission it. The project was, however, completed by a joint venture in less than ten years and $ 3.5 billion (DOE, 2013; Cameron and Lavine, 2006; Bodey, 2005/2006). Sellafield is a six square kilometers nuclear site in the UK that contains 99 percent of the UK

Table II. Benchmarking across decommissioning projects

	Nuclear	Non-nuclear
UK	Benchmarking NDPs across the UK	Benchmarking non-nuclear decommissioning projects across the UK
Non-UK	Benchmarking NDPs across several countries	Benchmarking projects across countries and in different industrial sectors

radioactivity. The UK Nuclear Decommissioning Authority estimates that it would take almost £120 billion and more than 100 years to decommission it (NDA, 2017). This can stimulate debate on project temporality (Brookes *et al.*, 2017).

Rocky Flats and Sellafield also present very different aspects. For instance, Rocky Flats stopped operations in 1989, and during its decommissioning, its waste was shipped to other countries in the USA. Conversely, Sellafield is still an operating nuclear site that handles radioactive material shipped both from other countries and other nuclear sites in the UK (Invernizzi *et al.*, 2017d).

Despite these differences, early results and "lessons learned" from this cross-comparison are remarkable. 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 and Lavine, 2006). This together with incentives singularly allocated to employees to promote feasible ideas can improve 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 comparable to Sellafield, Rocky Flats had a "buffer zone" which surrounded the site that proved to be helpful for the management of radioactive material (Cameron and Lavine, 2006). Sellafield, on the contrary, is "packed with buildings" (informal talks with Sellafield employees), which hinders the construction of new facilities to treat and confine the radioactive material.
- Early and timely engagement of stakeholders. Effective communication and the involvement of stakeholders in collaborative action support the smooth delivery of decommissioning projects (Invernizzi *et al.*, 2017c).

These empirically based lessons learned, together with good and bad practices gathered from the literature, are tested with the statistical analysis of step 4b.

4.2 Cross-comparison among Oil & Gas decommissioning projects

In 2015, the expenditure for offshore Oil & Gas decommissioning reached £1.1 billion in the UK and £1 billion in Norway, a considerable increase from the previous year, where £800 million and £770 million were, respectively, spent in the same countries in 2014 (Oil & Gas UK, 2016).

Similarly to NDPs, Oil & Gas decommissioning projects:

- have a multi-million budget;
- are partly funded by the government;
- are affected by a highly regulated environment;
- are affected by cost overrun and schedule slippage;
- have a potentially high environmental impact, as Natural Occurring Radioactive Material might build up, which might cause unexpected radiological issues; and
- are less uncertain than NDPs, but still are affected by high uncertainties.

Therefore, the lessons learned from these ten Oil & Gas projects (summarized in Table III) are also considered to populate the list of project characteristics whose correlation with the project performance can be tested through the statistical analysis. Indeed, most of the cost and schedule drivers highlighted in Table III are shared with the nuclear decommissioning industry.

Case study	Within budget?	Within schedule?	Cost and schedule drivers highlighted in the close out reports
Frigg Field (Total E&P Norge AS, 2011; Total E&P Norge AS, 2003)	No	Yes	More complex operation than originally foreseen; change in removal method
North West Hutton (NWH) (Jee, 2014; British Petroleum, 2006)	No	No	General lack of track record; lack of available benchmarking; pipeline cutting and removal taking longer than expected; additional vessel mobilizations were necessary; trenching activities took longer than scheduled due to the soil type encountered; delayed due to the intention to combine NWH decommissioning scope with other works to enable technical synergies and cost efficiencies
Indefatigable (Shell E&P UK, 2014; Shell UK Limited, 2007)	No	No	Costs figures to estimates cost were too old and not corrected with inflation
Linnhe Field (Shell E&P UK, 2014; Shell UK Limited, 2007)	No	No	Inclement weather; greater than estimated duration of the work; need of a guard vessel
Manifold and Compression Platform (MCP)-01 (Total E&P UK, 2013; Total E&P UK, 2007)	No	Yes	Additional engineering required to ensure a safe and stable removal activity; additional man-hours required to execute the significantly larger work scope; presence of hazardous materials not previously recorded on register gave increased activity both offshore and onshore; additional time at site required additional flotel attendance; more visits by heavy lift vessel required than had been estimated; the decision by the contractor to use the "piece-small" removal process on a large scale; difficulty to contract enough experienced and skilled labor; knowledge management; pre-qualification of "new" techniques should be conducted; control on the availability and reliability of cranes and tools
Kittiwake SAL Export System (Centrica Energy, 2012; Venture Production plc, 2009)	No	No	The over-spend related to the cost of preservation and onshore storage made necessary by early recovery (£0.4 m) and the weather delay during load in (£0.3 m); availability of a suitable vessel; potential synergies with other projects
Shelley (Premier Oil, 2015; Premier Oil, 2010)	Yes	Yes	The impossibility of utilizing water jetting methods; the re-use of end fittings to be re-used to make new jumpers; the complexity of the recovery of the "Polyoil" resin-based cable clamps, due to complete disintegration; the discharge of oil-based mud residue during the wellhead cut
Tristan NW (BRIDGE Energy, 2010; Silverstone Energy Limited, 2010)	No	No	Operational and extensive weather delays
Fife, Fergus, Flora and Angus (FFFA) (HESS, 2014; HESS, 2012)	No	Yes[a]	Additional scope of work
Camelot (Helix Energy Solutions, 2013; Energy Resource Technology Ltd, 2012)	Yes	Yes	Impact of processing naturally occurring radioactive material
Total positive	2/10	5/10	Only two of the Oil & Gas decommissioning projects were completed within the estimated budget. Five over ten were completed within the schedule

Note: [a]Not explicit
Source: UK Government (2017)

Table III.
Summary ten selected Oil & Gas decommissioning case studies

4.3 Example of results from the first iteration of the statistical analysis: the Fisher exact test

The aim of the statistical analysis is to highlight the correlation between the project characteristics and their performance. Table IV lists four country-specific independent variables, two of which resulted in being correlated with the project performance according to the first statistical test implemented (i.e. the Fisher exact test) to a pool of 30 NDPs. This is a preliminary result, applied on a pool of NDPs. This research aims to increase the number of NDPs to improve the reliability of the results of the statistical analysis.

5. Discussion and conclusion

Due to their techno-economic, political, and social magnitude, megaprojects have risen significant interest not only among practitioners, but also among academics. However, it is still extremely hard to gather good practices and develop empirically based guidelines in a systematic way.

This paper presents an innovative methodology based on benchmarking that combines qualitative and quantitative analysis to collect, select, and investigate good and bad practices and learn from a portfolio of (mega)projects. This methodology is exemplified using the case of decommissioning projects (and nuclear ones in particular), which are still remarkably under investigated, although extremely significant in terms of complexity and budget.

The methodology proposed in this paper starts with the selection of representative megaprojects and the listing of the project characteristics that impact on the project performance according to the literature. This literature is complemented by semi-structured interviews and followed by a qualitative analysis of the information collected. Then, this methodology suggests to apply statistical analysis to assess the correlation between project characteristics and their performance and to validate the results through pilot projects.

In particular, the Fisher exact test is envisaged to be applied first, as it is able to identify correlations within small data sets and to evaluate whether or not a single independent variable (e.g. a project characteristic) is associate with the presence (or absence) of a dependent variable (e.g. the project performance). The output of the test is a p-value, which represents how likely 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. Other statistical analysis and data mining techniques can be applied at later stages of the research.

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[a]	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

Note: [a]From Transparency International, as in Locatelli, Mariani *et al.* (2017)
Source: Invernizzi *et al.* (2017b)

Table IV. Example of independent variables statistically correlated to 50 percent cost overrun

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Note

1. "Correlation" is here used to explain the relationship between two variables, without specific reference to any linear relationship (i.e. as a synonym of the more generic term "association").

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(The Appendix follows overleaf.)

Appendix 1

Reference	Definition of benchmarking	Highlights relevant for the current research	Steps and/or phases of the benchmarking process
"The benchmarking book" (Stapenhurst, 2009)	Stapenhurst (2009) provides a list of definitions, finally summarizing benchmarking in the "method of measuring and improving our organizational performance by comparing ourselves with the best"	Stapenhurst (2009) provides a comprehensive investigation into the benchmarking analysis, focusing on the benchmarking process and the managerial and organizational aspects of benchmarking	Stapenhurst (2009) summarizes the benchmarking process into three main phases, i.e.: 1. Planning: develop a project proposal 2. Benchmarking performance: recruit and work with participants, collect and compare data 3. Improvement: improve the organization
"Benchmarking the benchmarking models" (Anand and Kodali, 2008)	According to Anand and Kodali (2008), the definition of benchmarking vary. Key themes include measurement, comparison, identification of best practices, implementation and improvement	Anand and Kodali (2008) highlight that there are many kinds of classification schemes for benchmarking and provides an overview of different classification schemes and types of benchmarking. In total, Anand and Kodali (2008) have investigated 35 published models The author provides a taxonomy for benchmarking models, dividing them into consultant/expert-based models, academic/research-based models and organization-based models, and finally states that benchmarking should at least be classified into internal and external benchmarking Anand and Kodali (2008) reveal the presence of 71 benchmarking steps in the 35 different publications analysed. In those, around 13 steps have been addressed by many researchers (> 40% of them) and are therefore called "common steps" of benchmarking. Excluding the "common steps", Anand and Kodali (2008) additionally lists 18 practices, that had an occurrence between 14% and 45%. Lastly, Anand and Kodali (2008) propose a 12-phases that include 54-detailed-step benchmarking model	Anand and Kodali (2008) highlight the 13 common steps of the benchmarking process: 1. Identify the benchmarking subject 2. Identify benchmarking partners 3. Perform benchmarking study 4. Determine current competitive gap 5. Establish functional goals 6. Develop action plans 7. Implement of action plans to bridge the gap 8. Recalibrate the benchmark 9. Understand the current situation by collecting and analysing the existing information on the subject to be benchmarked 10. Monitor results of the implemented actions 11. Identify the critical success factors or indicators of the subject to be benchmarked 12. Measure the existing state of the subject to be benchmarked with respect to the critical success factors/indicator 13. Form a benchmarking team and identify a leader of the team to carry benchmarking study
"Benchmarking as an action research process" (Kyro, 2004)	"Even though definitions vary between scholars, the aspects of evaluation and improvement by learning from others are embedded in the definitions regardless of the definer" (Kyro, 2004)	Adopting an interpretative, comparative concept analysis, Kyro (2004) suggests that benchmarking can be regarded as a special kind of action research. If so, the author affirms that, more attention should be put on "preliminary planning, observation, reflection and the use of theoretical frames". Kyro (2004) also provides a detailed comparison of benchmarking and action research, focusing on: (1) the similarity of their purpose, i.e. to improve practices, (2) the researcher's role, (3) how the processes take place and how they can be either adapted or created, (4) the phase of action research vs the phases of benchmarking	Kyro (2004) provides a review of benchmarking models and a classifications of benchmarking phases compared to action research. Kyro (2004) approaches the benchmarking process as a "two-cycle spiral, where the actual data collection phase is regarded as an action of the first cycle […] and at the same time is generic enough to be adopted for different forms of benchmarking"
"An evolutionary approach to Benchmarking" (Fernandez *et al.*, 2001)	"Benchmarking is the process that facilitates learning and understanding of the organization and it processes. It enables organizations to identify the key processes that need improvement, and to	Fernandez *et al.* (2001) propose an evolutionary classification method called cladistics, that distinguishes between different organisational types according to how they evolve and develop new ways of working. The authors firstly list the benchmarking styles (classified into internal, competitive, functional and generic and strategic), highlighting their advantages and disadvantages. Fernandez *et al.* (2001) also affirm that the benchmarking process is not "a universal yardstick, as it is impossible to establish an absolute measurement in the benchmarking process".	Fernandez *et al.* (2001) provide a structured literature review of 6 earlier publications on benchmarking models, highlighting the five generic steps of benchmarking models: 1. Planning 2. Analysis and data collection 3. Comparison and results 4. Change

Table AI.
"Benchmarking" in the literature

(*continued*)

	search for applicable solutions for the best in class" (Fernandez *et al*., 2001)	The author also state that benchmarking provides a "situational analysis", but not necessarily a "strategic roadmap". Of interest is the consideration that benchmarking models can be used to benchmark "both single functions and an entire organization" and that the reductionist approach (in opposition to the systemic approach) seeks to understand systems by reducing them into manageable individual parts	5. Verification and maturity
"Benchmarking in the UK: an empirical study of practitioners and academics" (Longottom, 2000)	Longbottom (2000) highlights respectively Camp's definition of benchmarking, as the "search for industry best practices that will lead to superior performance " (Camp, 1989)	Longbottom (2000) investigates the status of benchmarking within the UK through the analysis of answers to questionnaires (1,020 questionnaires were issued over a period of nine months, achieving a total response of 560). This study revealed that benchmarking is not so well-established as suggested by the literature, highlighting four major areas that require further discussion, i.e.: (1) the link between benchmarking and the strategic planning process; (2) the development of customer benchmarking methods; (3) the critical factors for transferring best practices across organizations, (4) the adaptation to post-modern attitudes to benchmarking	Longbottom (2000) identifies four major stages of the benchmarking process: 1. Planning 2. Analysis 3. Implementation 4. Review
"Benchmarking process formalization and a case study" (Büyüközkan and Maire, 1998)	"Benchmarking is the continuous process of evaluation of products, services and practices, with respect to those of the strongest competitors or of the enterprises recognized as leaders" (Büyüközkan and Maire, 1998, quoting Camp (1995)) "In a direct way, benchmarking is a process of evaluation and improvement of performance" (Büyüközkan and Maire, 1998)	Büyüközkan and Maire (1998) state that benchmarking is one of the most efficient and effective management tools to help an enterprise to improve its performance. The author also points out some of the obstruction against the benchmarking approach, e.g. industrialists that think that their business processes are very company specific and that it is not ethical to look at other companies' technology and manufacturing methodology, and the lack of formal benchmarking methodology Büyüközkan and Maire (1998) define a general benchmarking process to cover the different types of benchmarking (i.e. internal, external, industry, competitive, and generic benchmarking). This process is divided into the following 5 phase, divided into 15 steps and is a cyclical, "never-ending and learning" process. Büyüközkan and Maire (1998) also state the serious difficulties of implementing a continuous improvement activity is that "there are no standard performance metrics to be utilized in such studies" The author then illustrates the methods and tools for the first 5 steps of the benchmarking process through a case study	The 5-phase, 15-steps benchmarking process: 1. Self-analysis: a. Define the activities and customers of enterprise b. Determine performance criteria and performance measures c. Revise and improve current performance 2. Pre-benchmarking a. Establish priorities and choose benchmarking subject b. Choose benchmarking partners c. Determine methods and tools of data, information and knowledge collection 3. Benchmarking a. Collect and organize information b. Determine and analyse the performance gap c. Evaluate future enterprise realization 4. Post-benchmarking a. Communicate benchmark findings and establish functional goals b. Set objectives and develop action plans c. Implement specific actions 5. Observation and adjustment a. Review the benchmarking integration and learn the results b. Estimate success of the project and recalibrate benchmarks c. Adjust the objectives and return to step 1

Table AI.

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Appendix 2

Table AII. "Benchmarking" applied to the construction industry

Reference	El-Mashaleh *et al.* (2007)	Costa *et al.* (2006)	Ramirez *et al.* (2004)	Garnett and Pickrell (2000)
Aim of the research	The aim of this research is to present a comprehensive benchmarking model that uses input metrics (i.e. (1) safety expenses and (2) management expenses) and output metrics (i.e. (1) schedule adherence, (2) cost performance, (3) customer satisfaction, (4) safety performance, and (5) profit) to determine the company performance	The final aim of this paper is the comparison of four benchmarking approaches is to use the lessons learned and upgrade the existing benchmarking initiatives to devise new ones. All four initiatives use an interactive online tool for the collection and evaluation of the benchmarking measures	This research presents the results from the application of different benchmarking system through different methods: (1) the qualitative benchmarking with the class median, (2) the correlation analysis, (3) the factor analysis, (4) the multivariate linear regression, and (5) sector trends	This paper discusses the development and testing of a benchmarking model to be implemented in the construction industry. Benchmarking models which ranged from 5 step to 11 step processes are reviewed and the key features of each stage are highlighted
Method or model described or adopted	Firstly, this paper lists and criticizes three models that provide insight into overall firm performance and support trade-off analyses among multiple key performance metrics. These three models are criticized for (1) being project specific; (2) not supporting the understanding of the trade-offs among the different variables that affect the performance; (3) providing no insight into the relationship between how resources are expended and the relative success of out- comes; (4) not allowing the measurement of the impact of certain technological and managerial factors on overall firm performance Secondly, this paper proposes and describes a comprehensive model that uses (1) schedule adherence, (2) cost performance, (3) customer satisfaction, (4) safety performance, and (5) profit to assess the performance in the construction industry, since these appear to be the most critical to overall success. This comprehensive model also incorporate Data Envelopment Analysis (DEA) where the organization under study is called Decision Making Unit (DMU). DEA uses mathematical linear programming to determine which of the DMU under study form an envelopment surface, i.e. an efficient frontier	Firstly, this research revises the role of performance measurement in the benchmarking process and highlights the importance of abstraction of best practices before they are transmitted and applied in the company Secondly, four benchmarking initiatives were analysed: (1) KPI from the UK; (2) the National Benchmarking System for the Chilean Construction Industry (NBS-Chile); (3) the Construction Industry Institute Benchmarking and Metrics (CII BM&M) from the USA; and (4) the Performance Measurement for Benchmarking in the Brazilian Construction Industry (SISIND-NET Project) This paper highlights that the most common performance measures involved are cost and cost predictability, time and time predictability and safety	(1) Qualitative benchmarking with the class median is 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. The main steps of this analysis are: send questionnaire, collect data, calculate performance indicator per each company, compare with other companies performance. (2) Correlation analysis is used to investigate the intensity with which two variables, X_i and X_j, are linearly related. To measure the intensity of the correlation, the Pearson's coefficient is used. The correlations investigated are (2a) between indicators and management dimensions, (2b) for the central office, and (2c) for the construction site. The correlation analysis found that safety performance is strongly related to companies having superior planning and control, quality management, cost control, and subcontractor management policies. (3) Factor analysis is used (3a) for central office, and (3b) for construction site. The factor analysis uses the method of principal components to determine the underlying structure among the different management dimensions and identify relationships not previously established	This paper focuses on three main questions: (1) what is benchmarking? (2) How can it be used? (3) When can it be used? The authors also highlight the problems in benchmarking, i.e. (1) insufficient client resources, time, money, staff, etc.; (b) internal resistance; (c) previous bad experiences; (d) difficulty in identifying and obtaining partners; (e) 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 This paper compares different benchmarking models to subsequently define a 7–step model and case study analysis through action research. The authors highlight that, to be successful, the benchmarking process is as important as the benchmarks themselves. Another key strength of the methodology is that the theoretical basis is aligned with that of benchmarking, i.e. social constructivism instead of positivism. The difference in approach between benchmarks and benchmarking reflects the theoretical schools of positivism and social constructivism; the former being based on fact finding, the latter an interactive activity whose benefits are as much in the social interaction as the measurement process

(*continued*)

Steps of the analysis and highlights	The three benchmarking models are: Fisher *et al.* (1995) that collected data from 17 companies on 567 projects; Hudson and the Construction Industry Institute (1997-2000) that collected data of 901 projects from 37 owner and 30 contractors; and the Construction Benchmarking Programme or key performance indicator (KPI) model (1998)	The four methods are described. The barriers of the implementation of performance-measured systems in the construction industry arise because (1) the construction industry is a project-oriented industry with "unique" projects; (2) establishing a project performance measurement system and incorporating it into the company routine requires an intense effort; (3) the responsibilities for data collection, processing, and analysis, in general, are not well defined at the beginning of the project; (4) each project usually has a different managerial team and the use of measures will depend on the capabilities and motivation of each manager	The commonality table is one of the outputs of this analysis, and it represents the proportion of the variance explained by the component or factor. The factor analysis found that central office priorities focus on strategic management policies having longer-term competitive impact, while site management emphasizes tactical management dimensions having short-term impact (4) Multivariate linear regression was used but discarded due to the weak correlation coefficient caused by the reduced quantity of data. (5) Sector trends are used to categorize and analyse survey results according to construction industry subsectors. The main steps for this analysis are: prepare histograms of the responses to each questions, analyse responses firstly according to job category, secondly according to construction industry subsectors, draw conclusions. In the analysis of industry trends, construction companies working in the civil works and low-rise housing subsectors were generally found to lag management performance levels registered for the high-rise and heavy construction subsectors	The steps presented in this paper are: definition of the benchmarking model, collection of data for the case study analysis, description of the implementation of the selected case studies, presentation of the results obtained, that suggest that benchmarking could be a powerful tool in investigating and managing change on construction projects
Data collection and number of cases	The data were collected through a survey questionnaire that was divided into (1) collection of general information regarding the interviewee, (2) firm general information, (3) firm overall performance Data were collected from 74 construction firms, including general contractors, construction management companies, design/build firms, and subcontractors, involved in residential, commercial, industrial, and heavy/ highway construction. The minimum number of DMU in any model should be three times the number of variables, and the model's discriminatory power increases with more DMU and fewer variables	The information about the KPI was obtained from its website, published papers, and reports. For the CII BM&M, the information was obtained from its website, reports, and interviews with a project researcher and the associate director. The information about the NBS-Chile was obtained from its websites, from published papers and reports, and from its existing database. Also, semi-structured interviews were conducted with managers of seven construction companies involved in the program and the current coordinator of the initiative. Finally, two of the authors of the SISIND-NET Project have been directly involved in this project Different numbers of data per method are analysed	This paper advances the use of a structured questionnaire to evaluate aspects related to the organizational culture and management of construction companies The results of the questionnaire are then correlated against the quantitative performance indices obtained from the CDT's national benchmarking study to establish causal relationships 13 companies initially participated to the assessment, 42 questionnaires were completed by central office personnel and 87 by construction site representatives	2 case studies are analysed: construction retail client and research organization The authors stressed the fact that, "often data, loosely termed benchmarks, are determined by comparative analysis, experience and gut feeling rather than through focused analysis"

Table AII.

Publication II

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Managing social challenges in the nuclear decommissioning industry: A responsible approach towards better performance

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Abstract

At the end of their lifecycle, several large infrastructure will have to be dismantled, presenting unfamiliar challenges. Therefore, project management will need to focus extensively on the delivery of successful decommissioning projects to meet stakeholders' expectations and funding constraints. While there is an extensive literature that investigates the techno-economic aspects of decommissioning, social aspects remain remarkably under-investigated. Even if stakeholder communication, involvement and engagement are widely believed to be key enablers for the success of a project, often the needs and preferences of local communities are neglected and a participatory-based form of dialogue averted. Consequently, decommissioning projects fail to meet their intended objectives. Focusing on the nuclear decommissioning industry, this paper addresses the literature gap concerning social responsibility. A deductive method to formulate and validate theories regarding the social challenges for decommissioning is developed through a review and analysis of salient case studies.

Keywords: Stakeholder management; Decommissioning; Social responsibility; Participatory decision making; NIMBY syndrome

1. Introduction

Project management has, until now, mainly focused on new built. However, at the end of their lifecycle, most of infrastructures and industrial plants have to be dismantled. Therefore, in the future, project management will need to focus more and more extensively on the challenges imposed by decommissioning projects.

In particular, the decommissioning of mines (Nehring and Cheng, 2015; Franklin and Fernandes, 2013) and energy infrastructures such as large dams (Agoramoorthy, 2015; Oldham, 2009; Pacca, 2007), Oil&Gas platforms (Oil&Gas UK, 2015; Lakhal et al., 2009) and nuclear facilities (IAEA, 2016c; OECD/NEA, 2016; Laraia, 2012a), are likely to raise the biggest challenges not only from the economic perspective, but also from the socio-environmental one. Within these, the nuclear decommissioning industry is the most affected by decommissioning costs and socio-environmental impact, because of the activities connected with decommissioning and the complex regulations that establish the correct disposal of radioactive material. Indeed, nuclear infrastructures are extremely complex and various encompassing numerous types of facilities, such as Nuclear Power Plants (NPPs), fuel fabrications facilities and research centres.

Depending on their function, nuclear facilities' life cycle widely varies, normally lasting several decades. Primarily, the end of nuclear infrastructure's operational phase is due to uneconomical operation, technical obsolescence, safety consideration, or to the conclusion of the research programme (Laraia, 2012b).

Globally, costs estimates for Nuclear Decommissioning Projects and Programmes (NDPs) lie in the range of hundreds of billions of pounds, reaching for instance £ 55 billion in France (WNA, 2015c) and almost £ 70 billion (discounted) in the UK (NDA, 2016a).[1] NDPs have huge uncertainties that hinder the reliability of their forecasts and their schedules can

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[1] £ 53.2 billion for the decommissioning of Sellafield site alone, that is expected to last 120 years (NDA, 2016b).

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last decades, so several stakeholders are involved throughout the NDPs development. Consequently, it is important to evaluate the success of a project taking different stakeholders' point of view, according to a number of success criteria, in different timescales, as suggested by Turner and Zolin (2012), Müller and Turner (2007).

From the socio-economic perspective, some of the key enablers for the success of a project recognized in the literature are (Ruuska et al., 2011; Greiman, 2013; Zeng et al., 2015; NDA et al., 2015a):

- ➢ the local economy promotion, through allocation of benefits
- ➢ poverty alleviation through careful job repositioning, and
- ➢ effective stakeholder communication involvement and engagement.

However, as it happened in the construction of a waste repository in Scanzano Jonico (Bentivenga et al., 2004; Zinn, 2007), the needs and preferences of the local community are often still neglected and a participatory-based form of dialogue averted. NDPs fail to meet their scope and they are considerably delayed or even cancelled.

NDPs are morally troublesome also from an intergenerational perspective, as the benefits of nuclear power production are mainly for the present generation, while burdens (such as the remaining of long-living radiotoxic waste) could be transferred to the future generations (Taebi et al., 2012). In several countries the last generations (from the 50s to early 2000) enjoyed the creation of job positions and the availability of electricity, while the present and future generations will carry only the burden and costs of the compulsory nuclear sites clean-up and waste management.

This paper addresses the topic of social responsibility in decommissioning/dismantling projects. A deductive approach is adopted to formulate and validate theories regarding the social challenges that affect NDPs, and following the social constructionism approach, what people think and feel, both individually and collectively, is taken into account. This promotes a better understanding of the situation, incorporating the stakeholder perspective into theories. This analysis is based on a systematic collection of quantitative and qualitative data, so that theories can be critically framed into more formally defined constructs.

More specifically, this paper addresses two research questions:

- ➢ Which are the main social challenges that arise during the development of a NDP, and how do they affect NDPs?
- ➢ Which are the best practises to socially and ethically manage these challenges, and successfully meet the scope of the project?

NDPs are analysed because of their economical relevance, urgency to deal with radioactive material and the availability of public information. Nevertheless, lessons learned gained from NDPs are applicable to a number of decommissioning/dismantling projects in other industrial sectors, such as oil & gas, water infrastructures etc.

Since some NDPs are characterized by multi-billion budgets and have a high level of innovation and complexity, they can be addressed as megaprojects. Therefore, this paper is organized as follows: the literature review of section 2 starts with the analysis of social responsibility in major infrastructures, focusing on NDPs, and answers the first research question and identifies the main social challenges of NDPs and their consequences. Section 3 describes the research methodology for the collection and selection of the NDPs. Section 4 addresses the second research question and highlights the key factors to manage the risks for social responsibilities in order to successfully and ethically meet the scope of the project. Section 5 presents a deep reflection on the importance of stakeholder management and social responsibility in NDPs, highlighting best practises from international case studies.

2. Literature review

2.1. Social responsibility of major infrastructures

There is not a single accepted definition of major and mega projects in the literature: usually, megaprojects are characterized by budgets above $1 billion with an high level of innovation and complexity (Flyvbjerg et al., 2003; Locatelli et al., 2014a; Merrow, 2011; Van Wee, 2007). However, already in 1985, Warrack (1985) argued that $1 billion is not a constraint in defining megaprojects, as in some contexts, a much smaller project (such as one with a $100 million budget), could constitute a megaproject. Indeed, Hu et al. (2013) claim that a deterministic cost threshold is not appropriate for all countries, and a relative threshold such as the GDP should be used instead.

Existing studies on social responsibility of major infrastructures are still scattered and fragmented (Zeng et al., 2015) and concerns about social responsibility have grown significantly only during the last two decades. Craddock (2013) defines "*project social responsibility*" as "*the process to achieve the projects' objectives and balance the needs of all the stakeholders is an ethical manner to ensure that financial resources, human resources and environmental resources are utilized in a way that sustains all three*" and focuses on the business excellence models that contribute to project sustainability and project success. Wang (2014) adopts the stakeholders' perspective and investigates the relationship between megaproject crisis management and social responsibility: the author's conclusion suggests that a dynamic megaproject network governance mode can promote stakeholder engagement in collaborative actions and improve the effectiveness and efficiency of the delivery of the megaproject. Shen et al. (2010) highlight the importance of incorporating sustainable development principles during the feasibility study of a project, considering not only the economical perspective, but also the social and environmental one, emphasizing the pivotal role that the Government, clients, architects & engineers, contractors and suppliers.

Focusing on nuclear sites in the UK, Whitton et al. (2015) highlights an increase in dialogue with stakeholders, concluding that fairness and justice are necessary to promote a community and institutional awareness regarding social sustainability. In fact, businesses and organizations do not operate in a vacuum and "*their relationship to the society and environment in which they operate is a critical factor in their ability to continue to operate effectively*" (ISO, 2010). The nuclear industry, and the nuclear decommissioning industry in particular, suffers from the so-called "complex project environment" (Locatelli et al., 2014a,b).

Therefore, since NDPs usually involve large numbers of stakeholders and are (1) characterized by activities that range from small projects to major national multibillion projects; (2) at least partially commissioned by governments; (3) uncertain, complex and politically sensitive projects without fixing a deterministic threshold, this paper addresses NDPs as mega-projects (Turner, 2009; Flyvbjerg, 2014; Locatelli et al., 2014a,b; Brookes and Locatelli, 2015).

2.2. The relevance of nuclear decommissioning & its social implications

Nuclear decommissioning is a long, expensive and complex set of processes with a multidisciplinary nature. 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 […]*"* and can *"be concluded without dismantling, if the existing structures are for another use"* (IAEA, 2016b). Decommissioning, waste management and site remediation, are the main phases to restore the nuclear site to new use, which is not necessarily identical to its original state. However, in the nuclear decommissioning industry, the boundaries between "decommissioning projects" and "waste management projects" are blurry and hard to distinct. Therefore experts often refer to them as "waste-lead decommissioning projects" and the literature includes the management of radioactive wastes within the NDPs costs estimate (OECD/NEA, 2012). This causes a scope definition and management issue due to the lack of a clear description of what a "decommissioning project" and "waste management project" is. This can also create confusion regarding the differences of a NDPs (with a clear end, e.g. the removal of a certain amount of radioactive material or the construction of a waste repository) and nuclear decommissioning operations (the continuous process of handling radioactive material, both legacy and continuously generated). This paper focuses on the NDPs highlighted in Fig. 1 (see the red circle), i.e. with the NDPs that deal with the existing legacy (i.e. the decontamination, de-energizing, dismantling and demolition of existing infrastructure) and the construction of new facilities (i.e. for the management, storage and disposal of radioactive material). Site restoration projects and the operations concerning the management of radioactive material that arise from nuclear decommissioning activities (see the red arrows) and the normal operation of nuclear facilities will be the topic of following researches.

Scope management significatly impacts on the NDP. In fact, the inclusion or exclusion of work packages, such as the fuel removal (NRC, 2016) or the complete dismantling of the plant (IAEA, 2016b), have an impact both in terms of budget and schedule and of social implications, e.g. the balance between the money spent vs the money to be spent, and the legacy left to future generations. Radioactive material (e.g. high-level-waste) are dangerous for thousand/hundreds of thousands of years, representing a relevant intergenerational equity issue. So, future generations will have to deal with this material for very long time, without benefit and even bearing the risk of terroristic

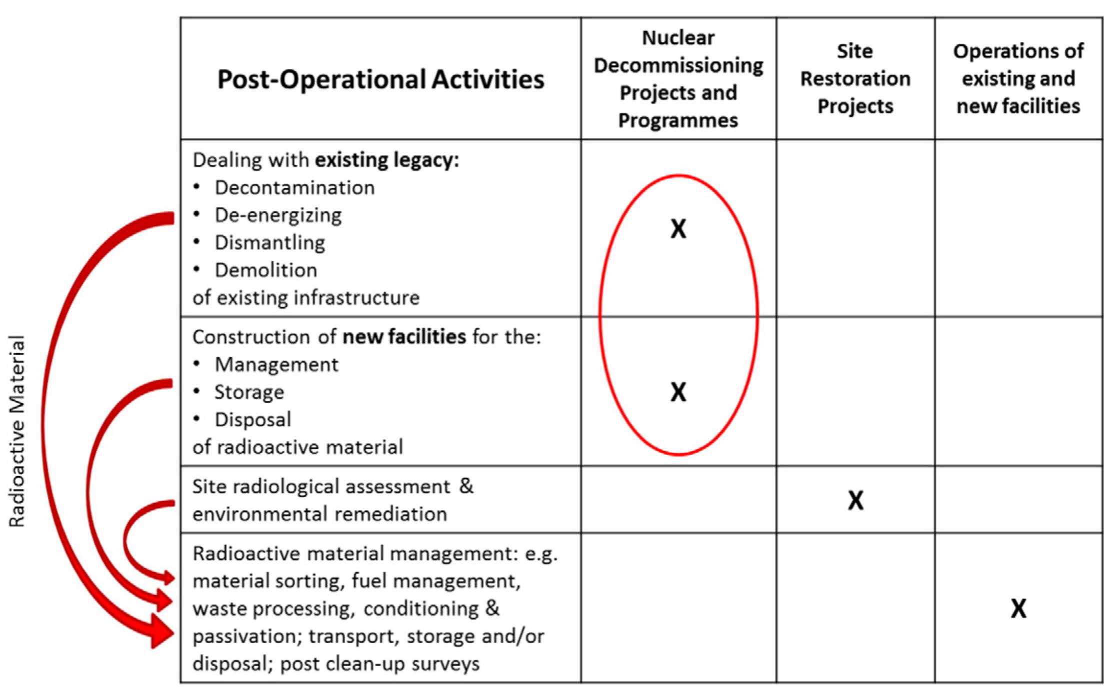

Fig. 1. Nuclear post-operational activities, adapted from (UK T&I, 2013): the red circle highlights NDPs, i.e. the focus of this research.

attack (POST, 2004). Indeed, this occurs not only when the facilities are operating but also when the facility is shut down, and the radioactive material has to be handled, reprocessed, transported, stored and disposed.

In contrast to the construction of a NPP, which is not compulsory since another type of power plant (e.g. Gas power plant) could be potentially be built instead, NDPs are mandatory both for safety, ethical and regulatory reasons. Remarkably, at the end of the construction of a NPP, new job positions are created, and the local community could take advantage from other benefits, such as the reduction of the electricity prices. Conversely, at the end of a NDP, there is no direct cash in-flows and the surrounding community could also be left with the legacy of radioactive waste.

Moreover, compared to other decommissioning projects, NDPs present unique characteristics. Firstly, several Oil&Gas facilities have already been safely removed (more than 100 only over the past decade in Golf of Mexico (Lakhal et al., 2009)), while the number of completed NDPs is negligible, being the fully completed decommissioned civil nuclear power reactors only 16 of the 150 that ceased operations (OECD/NEA, 2016). This hinders the process of applying lessons learned from past experience and increases the challenge to create trust within the local community, as it is impossible to demonstrate that the same NDP has been already performed safely before. Furthermore, the time scale for other decommissioning projects lays in the range of months-years, while decommissioning nuclear facilities can take decades, which requires a continuous and strenuous involvement of stakeholders. Furthermore, the possibility of recycling materials during the decommissioning of non-nuclear facilities is an established practice (e.g. the metal and concreate of civil infrastructure such as dams and long bridges) and could be a source of revenues for cost models that are based on the weight of material removed (Lakhal et al., 2009). Conversely, the recycling of nuclear material is hindered by extremely strict policies and technical constraints. Only few "win–win" shipment agreement exists, as highlighted by the swap deal between the UK and the US, where 700 kg of enriched uranium were shipped from Sellafield, UK, to the US in exchange of American nuclear material that will be used in the treatment of cancer patients across Europe (The Independent, 2016).

On the basis of the aforementioned literature and of interviews with experts, two major challenges that undermine the development of the NDPs stands out, i.e.:

1) personnel transition;
2) public unacceptance.

These two challenges directly affect the employees and the local community surrounding the NDPs, described as the "*the group of personal actors potentially concerned by, or who may become involved in, deliberations about radioactive waste management facility siting and operations*" (OECD/NEA, 2015a). The first major social concern is the so-called "personnel transition". Indeed, the transaction from the operations of a nuclear facility to its decommissioning requires major organizational changes. Personnel transition concerns retraining of the employees, restructuring of the management, creation of alternative employment and development of compensation strategies to dismiss employees (Negin and Szilagyi, 2012). This transition affects staff morale and commitment, as employees have to deal with new and unfamiliar, technical and organizational problems (Negin and Szilagyi, 2012). Moreover, the downsizing of the workforce socially affects the citizens surrounding the nuclear site, mostly because some workers cannot find a new employment in the community and are forced to relocate. Real concern also exists regarding the willingness of individuals to change from operators to decommissioning workers and to accelerate work that would result in more rapidly putting them out of a job (ITRC, 2008).

The second main social concern is the limited public acceptance of the local community facing the decision of building new nuclear facilities during the development of NDPs, such as a nuclear waste repository. Public unacceptance is generated by factors such as fear, lack of knowledge and low public participation (Devine-Wright et al., 2010), and is likely to cause the rejection of a project before it begins, or its interruption during its development. In the case of Japan, this "Not In My Back Yard (NIMBY) syndrome" has proved to cause an acceptance drop to less than 20%, if the repository is to be installed near the respondents' residency (Gallardo et al., 2014). Gallardo et al. (2014) also underlines the split between the general and the local interest, where the benefits of having a repository are widespread at national level but the costs are absorbed by small local communities.

Radioactive waste management is one of the main challenges connected to decommissioning. It includes sorting nuclear waste by degree of contamination, its deployment in apposite containers and its monitoring over an extended period of time in a long-term storage repository. Radioactive waste management issues are embedded in broader societal issues, i.e. environment, risk, sustainability, and energy and health policy (OECD/NEA, 2015b) and it is recognized as a complex decision-making-process that embraces social aspects as well as techno-economical ones. Early engagement with stakeholders and high level of communication maximizes the chances to receive higher degree of acceptance and reduce the unexpected complaints that would prevent the development of the NDPs from proceeding smoothly (McIntyre, 2012).

Due to personnel transition and public unacceptance, the socio-economic impacts of the implementation of NDPs has to be carefully evaluated, and the optimum decommissioning strategy have to be determined not only focusing on policy, safety, financial and technological constraints, but also involving employees and the local community surrounding the nuclear facility.

2.3. Stakeholder management to tackle the social challenges of NDPs

Project stakeholder management includes the processes that "*required to identify the people, groups, or organizations that could impact or be impacted by the project, to analyse stakeholder expectations and their impact on the project, and to develop appropriate management strategies for effectively engaging stakeholders in project decisions and execution*" (PMBOK, 2013). Stakeholder management has been vastly investigated in the literature, as shown by Mok et al. (2015) in their review of publications on mega construction projects published from 1997 to 2014.

In the decommissioning industry, the IAEA (IAEA, 2009) lists technical, economic, social and environmental stakeholders, while Love (2012) suggests classifying stakeholders into statuary consultees (government, health and safety regulators, environmental regulators, local authorities, #legal representatives) and non-statuary consultees (direct employees, contractors, non-government organization, local communities, local residents).

Concerning the ways to meet stakeholders' expectations and request, the three "pillars of trust", i.e. safety, participation, and local development could be implemented (NEA/RWM/WPDD, 2007). This is explained by the fact that (NEA/RWM/WPDD, 2007):

- ➢ safety is paramount and it is necessary for any individual to be able to act, take decisions and make use of their freedom;
- ➢ participation is fundamental to involve local politicians or community leaders, providing them with transparent information about plans and programmes and being constantly available to answer their questions;
- ➢ local development is needed to ensure high quality of life in the host community.

Whitton et al. (2015) highlight the importance of embracing the move towards a participatory-based form of dialogue in decisions rather than an expert-led form of consultation. Innes and Booher (2004) state that legally required participation methods can be counterproductive, but that key elements are authentic dialogue, networks and institutional capacity. LaGuardia and Murphy (2012) affirm that *"a lack of consideration of social needs can create political problems within the local population and significantly hinder the acceptance of a project"*. Also future generations are significantly affected by the development of NDPs, and the concept of intergenerational equity originates from the idea that the benefits of nuclear power production are mainly for the present generations, while the burdens of nuclear waste are transferred to the future (Taebi, 2012). In addition, energy policy institutions have operated out of the public eye and with minimal public involvement, and now face new challenges as the public becomes more attentive and responsive to energy choices (Miller et al., 2014).

In the nuclear decommissioning industry, stakeholders' management is also hindered by the peculiar characteristics of NDPs and the complicated interrelationships among various stakeholders. Indeed, nuclear facilities are usually built in remote areas and the local community strongly relies on the activities of the nuclear facility and benefits from lower energy costs and compensation from the government. One prime example is represented by Dounreay nuclear site in Northern Scotland, where the decommissioning programme accounts for one in every three local jobs (Beckitt, 2012) and the compensation from the government reaches £ 2 million to boost the workforce skills (Dounreay News, 2011). In the UK, the Nuclear Decommissioning Authority (NDA) sets three methods of supporting socio-economic activities, i.e. direct NDA funding, support through NDA operations, and funding Dounreay Site Restoration Ltd. to deliver Socio Economic activities (NDA et al., 2015b). The remoteness of the facilities is typical of the nuclear industry, as several nuclear sites were selected mainly according to the orography of the area, the distance to major population centre and the overall lower population density.

So, during the lifecycle of a nuclear facility several hundreds of people are engaged in the operations of the nuclear facility. The local community heavily relies on the operations of the nuclear site. When the nuclear facility has to shut down, the personnel transition is a complicated task, and affects not only the employees, but also their families and all the local community surrounding the nuclear site. In particular, when the nuclear facility stops operations, decommissioning experts are needed to help the transition, so the numbers of employees firstly slightly increases and then starts decreasing with the progress of decommissioning, as exemplified in (IAEA, 2011b). If this transition is not carefully managed, it would cause personnel dissatisfaction and widespread discontent.

The central feature of social responsibility is the willingness of an organization to incorporate social and environmental considerations in its decision-making process (ISO, 2010). Therefore, since the local community is likely to affect the outcome of a NDP, a systemic and sustainable approach and a societal dialogue is needed to inform and engage the stakeholders (Whitton, 2011), stakeholders' needs and preference have to be carefully addressed.

3. Method

Embracing the principle that the reality is determined by people, and willing to take into account what people think and feel, both individually and collectively, the social constructionist approach has been adopted in this research. This approach increases the general understanding of the situation incorporating the stakeholder perspective into theories (Easterby-Smith et al. 2012). To add authenticity and reliability to the research methodology, we address social responsibility challenges in NDPs through the cross-cases analysis (i.e. NDPs delivered in different countries). The approach adopted in this paper is based on the seminal work of Eisenhardt (1989) who derived a process where theoretical generalizations could be generated from reviewing a set of cases of a particular phenomenon. She also discusses "*reaching closure*," i.e., "wh*en to stop adding cases, and when to stop iterating between theory and data*". Eisenhardt (1989) advises researchers to stop adding cases upon reaching theoretical saturation and/or when the incremental improvement to quality is minimal. Four to ten cases usually work well because too few cases will be insufficient for empirical grounding and generalization and too many cases will be overly complex in terms of data management. In our effort to generate evidence, we reached 10 NDPs.

In particular, the criteria for the NDPs selection were:

- ➢ The project is a NDP, either dealing with legacy (to be decontaminated and dismantled) or construction of new

facilities (for the storage and disposal of radioactive material), as highlighted in Fig. 1;
- The project faces social risks during its development;
- The project is as recent as possible;
- The projects present international experiences, and the different ways in which the social challenges of NDPs have been addressed in different countries;
- There is enough official, reliable, and publically available information regarding the NDP.

Considering that the nuclear decommissioning industry is at its early stage of development, our collection of case studies virtually represents all the recent NDPs where public information are available in the European context.

The data and information collected, selected and analysed are mostly qualitative, since quantitative indicators are not fully practical and suitable for this kind of research (Labuschagne and Brent, 2008). Factors that have been evaluated are:

- stakeholder reactions to the communication of the NDP;
- protests arisen and the participation of the local community to these event;
- the percentage of workers employed in the nuclear facility prior shutdown compared to the number of relocated jobs after the shutdown;
- re-training activities that have been planned and performed;
- activities to inform and educate the local community;
- society and compensation mechanism developed for workers & the local community

Clear signs of aversion to nuclear power are also investigated, and highlighted by factors such as the outcome of referendum (e.g. the one hold in Italy, respectively after Chernobyl and Fukushima accidents).

4. Results

4.1. NDPs social challenges & their consequences

Personnel transition and public unacceptance are the major social challenges that are likely to arise during the development NDPs, as explained in section 2. Following the methodology described in section 3, a purposive sample of the NDPs has been collected, selected and summarized in Tables 1 and 2, to highlight that personnel transition and public unacceptance have respectively the following consequences, i.e.:

1) Underestimated socio-economic personnel costs;
2) abandonment of the project.

4.2. Underestimated socio-economic personnel costs

The first social challenge of NDPs is the risk of underestimating personnel transition costs, mainly caused by the need of staff retraining (Negin and Szilagyi, 2012), redeployment (NDA, 2012), the employment of new specialized staff (Devgun, 2012), and organizational changes.

The abrupt shutdown of the two units of Kozloduy NPP in Bulgaria exemplifies this challenge. In Bulgaria, the shutdown caused an unexpected reduction in the need of personnel and led to a decline in motivation due to frustration, fear of change and a loss of confidence in management. To tackle this, a training centre for the employees was established, but more absenteeism and increase in stress were still reported (IAEA, 2009). Since Kozloduy NPP was affected by early shut down and it is a heavy financial burden for the country, the EU provided financial support (IAEA, 2009), and the decommissioning licence for Kozloduy NPP was issued in 2014 (WNN, 2014). Ignalina NPP in Lithuania is another example of geographically and socially isolated NPP. Its closest town, Visaginas, has been hardly hit by the closure of Ignalina NPP, and has suffered not only by the decline in staffing and prestige of its largest employer and the loss of the original reason for the town's existence, but also from a near 5-fold rise in heating prices and similar trends of electricity prices (Ministry of Energy, 2011). The European Union has accepted to bear the economic and social impact of Ignalina NPP closure (Öko-Institut, 2013), since without sufficient funding the whole NDP would require even greater financial resources and longer time, staff expertise would be lost and social tensions would exacerbate in the region. Also, in Greifswald, Germany, activities such as re-training for the employees, education for new jobs and the adoption of retirement scheme have been undertaken (Backer, 2012b). However, there was a decrease of working moral and productivity, increase of unemployment, decrease of tax yields, less opportunities for investments, and one of the substantial problem was ensuring the acceptance of the public (Backer, 2012b).

Conversely, the Barsebäck NPP case, in Sweden, is a meaningful example of positive outcome of a sensible management of staff to maintain the feeling of personnel security: this was achieved through 3 to 5 years of employment guarantee before the reactor was closed and several initiatives such as individual supportive discussion (Lorentz, 2009; IAEA, 2008b). Similarly, at Vandellós-I, in Spain, the ENRESA[2] mitigated the negative socio-economic impact of the NPP shutdown hiring local and provincial companies (65% of the employees) and implementing a complete training plan to provide the workers with the necessary knowledge (NEA/RWM/WPDD, 2007; ENRESA, 2007). Here, employment was perceived to be the main local concern, especially as staff numbers have dropped from 350 when the plant was operational to about 100, and would reduce to 50 during the latency period (Bond et al., 2004).

A similar approach had already been taken in the UK during the transition from operation to defueling (and subsequent decommissioning) of the Trawsfynydd nuclear site (Jones, 1993). In Trawsfynydd, the consultation strategy started with the identification of three groups on whom the decommissioning was likely to have an environmental and socio-economic impact, i.e. employees, people living within 25–30 km radium from the nuclear site, and the locally elected council. These groups were

[2] The National Enterprise of Radioactive Waste, in Spanish is called Empresa Nacional de Residuos Radiactivos (ENRESA).

Table 1
Selected NDPs.

NDP	Country	Site		Scope	Stakeholders' reactions and NDPs progress	Key reference
		Pre-project	Post-project			
Kozloduy —1 & 2	Bulgaria	Brownfield (6 units on site)	Brownfield (Units 1, 2 ,3, and 4 were shut down before 2006. Unit 5 and 6 are still operating)	Decommissioning of unit 1 & 2 of Kozloduy NPP	Disputed BUT progressed	WNA (2016a), WNN (2016), EU (2013a, 2015), Öko-Institut (2013), IAEA (2009), Kozloduy NPP Plc (2008), IAEA (2008b)
Ignalina —1 & 2	Lithuania	Brownfield (2 units on site)	Brownfield (buildings that can be re-used will be preserved (INPP, 2016))	Decommissioning of Units 1 & 2 Ignalina NPP	Disputed BUT progressed	WNA (2016b), EU (2013a,b), Öko-Institut (2013), Ministry of Energy (2011), IAEA (2009)
Superphénix	France	Brownfield (NPP in operation)	Brownfield	Decommissioning Superphénix NPP	Disputed BUT progressed	EDF (2014), Tompkins (2011), IAEA (2008b)
Greifswald — 8 units	Germany	Brownfield (NPP in operation)	Brownfield (The site will distrubute natural gas, process renewable raw material, produce large components for shipbuilding.)	Decommissioning Greifswald NPP	Disputed BUT progressed	Bäcker (2012, 2012a, 2012b), IAEA (2008a,b, 2011a)
Vandellós-I	Spain	Brownfield (NPP in operation)	Brownfield (the reactor building will ramain in a "dormancy" for 25 years)	Decommissioning Vandellós-I NPP	Accepted AND progressed	WNA (2016c), NEA/RWM/WPDD (2007), ENRESA (2007), Bond et al. (2004)
Barsebäck — 1 & 2	Sweden	Brownfield (NPP in operation)	Brownfield (the demolition of the facility will await the construction of a storage facility, scheduled to be ready in the 2020s)	Decommissioning of Unita 1 & 2 Barsebäck NPP	Accepted AND progressed	Lorentz (2009, 2014), IAEA (2008b)
José Cabrera	Spain	Brownfield (NPP in operation)	Greenfield (Waste stored waiting for the repository)	Decommissioning José Cabrera NPP	Accepted AND progressed	OECD/NEA (2016), IAEA (2016a), WNA (2016c), IAEA (2011a)
Trawsfynydd	UK	Brownfield (NPP in operation)	Brownfield (NPP buildings in "care & maintencance")	Decommissioning Trawsfynydd NPP	Accepted AND progressed	Hyder Consulting Limited (2010), NDA (2009), Bond et al. (2004), Jones (1993)
Scanzanio Ionico	Italy	Greenfield (No nuclear site)	Brownfield (nuclear waste repository would operate)	Construction of national waste repository	Disputed AND abbandoned	IAEA (2009), Zinn (2007), Bentivenga et al. (2004)
Onkalo, Olkiluoto	Finland	Brownfield (NPP in operation)	Brownfield (NPP in operation and waste repository)	Construction of national waste repository	Accepted AND progressed	WNN (2013, 2015a,b), EU Committee (2006)

Table 2
NDP characteristics and their impact on the project outcome.

NDP		NDPs' promoting factors			Stakeholder reaction	
		Early and timely engagement with the local community	Start the NDP planning soon as possible, even better, when the facility is still operating	Privilege the siting of a waste storage/repository where a nuclear licence has been already provided	Positive	Negative
Transition from operation to decommissioning	**Kozloduy — 1 & 2**	–	–	X There is a low and intermediate level radioactive waste treatment and storage facility on site (WNA, 2016a)		**X**
	Ignalina — 1 & 2	–	–	X There is a final repository for low- and intermediate-level waste near to Ignalina NPP (WNA, 2016b)		**X**
	Superphénix	–	–	X France has along history of nuclear power production and the country benefits from low and intermediate level waste repositories and high level waste storage systems (EDF, 2014)		**X**
	Greifswald — 8 units	–	–	X The need to build an integrated interim storage facility for waste and fuel on-site is recognized as a cornerstone fro decommissioning (IAEA, 2008b)		**X**
	Vandellós-I	X As highligthed in (ENRESA, 2007), (NEA/RWM/WPDD, 2007), (Bond et al., 2004)	Vandellos-I was shut down on July 31, 1990, following a fire in one of its two turbogenerator in October 1989. The decommissioning plan was submitted by ENRESA to the Ministry in 1994 (Bond et al., 2004).	X Vandellos-I is now in "latency" and works as temporary storage facility for the graphite of the NPP (ENRESA, 2007)	**X**	
	Barsebäck — 1 & 2	X As highligthed in (Lorentz, 2009), (IAEA, 2008b)	X As highlighted in (Lorentz, 2009), (IAEA, 2008b)	X Some low-level waste is disposed of at reactor sites, and some is incinerated at the Studsvik RadWaste incineration facility in Nyköping (WNA, 2016d)	**X**	
	José Cabrera	X As highligthed in (IAEA, 2016a), (IAEA, 2011a)	X As highlighted in (WNA, 2016c), (IAEA, 2016a)	X Low and intermediate level waste is sent to El-Cabril. High level waste is stored on site (WNA, 2016c)	**X**	
	Trawsfynydd	X As highligthed in (Jones, 1993), (NDA, 2009)	X As highlighted in (WNA, 2015d), (NDA, 2009)	X UK has along history of nuclear power production and the country benefits from low and intermediate level waste repositories and high level waste storage systems (WNA, 2015d)	**X**	
Search for the siting of a nuclear waste repository	**Scanzanio Ionico**	–	–	The selected site has not previously been granted any nuclear licence (Bentivenga et al., 2004)		**X**
	Onkalo, Olkiluoto	X As highligthed in (WNN, 2015b), (WNN, 2015a), (WNN, 2013)	X	X Finland benefits from low and intermediate level waste repositories that have been operating sincemore than two decades (WNA, 2015a)	**X**	

separately consulted, they were handed information material, and a questionnaire. The questionnaire results pointed out that the major concern regarding the decommissioning phase was the job creation for local people. Staff was counselled regarding their personnel preferences, and they were offered the following choices:

- ➢ relocate to a different site within the company;
- ➢ leave the company on selective voluntary severance, an approach that give mutual benefit to the company and the employee;
- ➢ remain at Trawsfynydd for defueling work and eventually subsequent decommissioning.

Even if social groups within communities have different priorities (Whitton et al., 2015), the Trawsfynydd staff management proved to be efficient, with 75% of people allocated to their first choice, and only 10 employees of the original workforce of 487 employees affirmed to be "*significantly dissatisfied*" of their final allocation (Jones, 1993).

4.3. Abandonment of the project

The second social challenge of NDPs is the abandonment of the project, which can be caused by public unacceptance and local opposition. A radioactive waste repository has to be "hosted" by the local community for a very long time, so a collaborative and sustainable relationship must be established with the residents from the early stage of the development of the NDP. This improves both the ongoing quality of life of the host community and future societal capacity to contribute to the oversight of the facility (OECD/NEA, 2015a).

One negative case is the siting of the waste repository that was planned to be built in Scanzano Jonico, in Southern Italy. The choice of the Italian Government to identify in Scanzano Jonico the site for nuclear repository arose from the need to unlock a ten-year temporary situation in the management of radioactive waste. This waste is a legacy of the Italian NPPs (shut down after the referendum of 1987 after Chernobyl accident) and of research & medical activities. Italians already expressed clear sing of aversion to the nuclear industry through the referendum against nuclear power, and the communication of the site selection came totally unforeseen for the citizens of Scanzano Jonico, who were totally unprepared and uninformed of the topic. This completely unexpected communication was made through Law Decree 314 of the 14th of November 2003 and caused the rise of critics and protests from the local community that lasted several days (Bentivenga et al., 2004; Zinn, 2007). The main reasons that led to the failure of the initiative of Scanzano Jonico were the lack of early and timely involvement of the local community, exemplified by the complete absence of initiatives of communication to the public prior to the choice, and the general lack of trust in the institutions, strengthened by the procedure of the site selection. The arisen protests caused not only a delay in the project, but also the total removal of the assignment to Scanzano Jonico and the abandonment of the whole project. A similar matter occurred during the search for the siting of the Japanese geological disposal facility for spent nuclear fuel, where surreptitious deals not open to public produced surprise, anger and unacceptance when discovered by the local community (Lawless et al., 2014). On the contrary, the scoping project regarding the geological disposal in Finland (the Onkalo NDP) (WNN, 2015a, 2015b) shows how the dialogue with stakeholders improves the decision-making process and that the search of public consent through public engagement is essential to proceed with construction. Onkalo NDP is, in fact, a positive example of successful search for the repository of spent nuclear fuel and nuclear waste, and a repository is currently under construction at Olkiluoto nuclear site. Due to the Finnish open and transparent policy and the overall trust in the public authorities, no major protests of the local community have arisen (EU Committee, 2006). In May 1991 the government approved plans for a geologic repository; then, after twenty years of consultation, the repository was sited at Olkiluoto (EU Committee, 2006); in February 2015 the regulators approved the waste repository plan (WNN, 2015a), and the construction licence was granted in November 2015 (WNN, 2015b). Also in Sweden, the engagement of the local community resulted fruitful for the siting of a high-level-waste repository and two municipalities voted to candidate for the deep geological repository and received the support of more than the 75% of the population (WNA, 2015b).

4.4. Guidelines to address the social challenges of NDPs

The aforementioned consequences of NDPs social challenges can cause the delayed or abandonment of the NDP. However, relevant considerations can be drawn to build guidelines and develop future public participation strategies. In particular, it is worthwhile to highlight the following NDPs' promoting factors, i.e.:

- ➢ Engage and involve early and timely the local community;
- ➢ Start the planning of the NDP as soon as possible, possibly when the facility is still operating;
- ➢ Privilege the siting of a waste storage/repository where a nuclear licence has been already provided (e.g. for nuclear power production).

These considerations are supported by the NDPs analysis that shows that:

- ➢ avoiding the engagement with the local community causes demonstrations and protests from the local community and can lead to the rejection of the project; and
- ➢ starting the planning of NDP after the end of the operations of nuclear facilities does not facilitate the acceptability of the NDP, both if it is related to the dismantlement of a nuclear facility (e.g. Ingalina and Kozloduy) and the siting of a waste repository (e.g. Scanzano Jonico).

These findings are consistent and complement the best practice concerning public participation, and corroborate existing theoretical best practices, confirming that "*only when nuclear experts can withstand public challenges, they will gain and keep public trust in their judgement*" (Lawless et al., 2014). Consistently with Bond et al. (2004), this research also shows that if the decision-making process is transparent, the public feel that their legitimate concerns have been addressed. Moreover, in order to tackle the social challenges of personnel transition and public unacceptance while still maintaining a broad overview, the empirical evidence collected in this research suggests:

- ➢ Firstly, to consider the stakeholders logistically closer to the nuclear facility and cluster them into the following groups, i.e. direct employees (e.g. staff involved in daily operations), indirect employees (e.g. suppliers), associate (e.g. unplanned maintenance), workers at the local community (e.g. school teachers), and others (e.g. retired people) (IAEA, 2008a, 2009);
- ➢ Secondly, to engage with stakeholders in institutionalized dialogue and timely involve the local community to avoid surprise prevent reluctance in accepting the NDPs;
- ➢ Thirdly, manage the decrease of staff needed during the decommissioning phase also according to the individual needs and preferences, and engage the remaining staff in the decommissioning activities, both through economic incentives and psychological help. as suggested by Campbell (2007).

These considerations regarding a socially-responsible management of all the major stakeholders can reduce both the risk of local opposition and the risks of incurring on higher personnel transition costs. The empirical evidence validates and updates the earlier findings regarding the need to increase the public acceptance and satisfaction in the attempt to avoid social issues to arise. This is congruent with human resources management, that traditionally has had two roles: a “management support role”, i.e. providing the organization with competent people to undertake the work processes, and an “employee support role”, i.e. caring for the well-being of employees (Turner et al., 2008).

The organizational design during of NDPs is extremely relevant and is a dynamic entity that continuously evolves depending on the progress of the work. The management team should focus on both the alignment of the number (and skills) of people necessary during the decommissioning phase to accomplish the decommissioning tasks, and the employees’ necessity and preferences in terms of possible relocation. In particular, the decrease in the number of required staff for the decommissioning activities should be as aligned as possible with the numbers of people that leave. On one side, senior people should be provided with the opportunity to benefit from early retirement, while on the other side, according to their preferences, younger and more employable people should be given the possibility to relocate or to decide to remain so that their experience is retained. The decrease of employee during the transition from operations to decommissioning should be as gradual as possible, and a long-term government financing scheme should be put in place to guarantee the lowest possible impact on the local community: in some cases, early decommissioning could be preferred to maximize jobs and local income after the end of operations. Additionally, the management board needs to address the fact that workers are not just “industrial assets” but human being with a complex mix of feelings and aspiration, and should be treated according to their needs and necessities in every stage of the development of the NDP. Even if the implementation of these principles is likely to slightly increase the estimates for overall decommissioning costs, it will put the companies involved in the NDP into a stronger position, and the NDPs is more likely to receive consensus. These guidelines can be incorporated by the project management team during the decision making process to improve the planning and delivery of NDPs.

5. Discussion and conclusions

Historically, project management has focused mainly on construction projects. However, at the end of their lifecycle, several industrial plants and energy infrastructures in particular, have to be dismantled. Therefore, project management needs to learn how to face the unfamiliar challenges arising from decommissioning projects, both technical and socio-economic ones.

Within other decommissioning projects, NDPs are the most likely to be heavily affected by decommissioning costs, due to the imperative safety regulation, the long schedule and the number of stakeholders involved. Moreover, due to the large variety of both their design and purpose, nuclear facilities are characterized by an extreme complexity and variety, therefore their decommissioning presents huge challenges.

This paper, embracing the principle that the reality is determined by people and willing to take into account what people think and feel both individually and collectively, adopts and applies the social constructionist approach. This empirically-based cross-case analysis highlights the major NDPs social challenges, i.e. personnel transition and public unacceptance. Personnel transition concerns the re-training for part of the workforce, the development of compensation strategies to dismiss the rest of the workforce, the creation of alternative employment, and restructuring the management. Public unacceptance is generated by factors such as fear, lack of knowledge, low public participation and is one of the causes of the so-called NIMBY syndrome, where fear caused by the perception of risk is likely to cause a significant acceptance drop.

The literature review, the interviews with experts and the analysis of the 10 NDPs showed how the personnel transition and public unacceptance can hinder the smooth progress of NDPs. These two major social challenges have dramatic consequences on the development of a NDP and can respectively cause higher personnel costs and the abandonment of the project. From this analysis, the following project management considerations can be made, i.e.:

1) Engage and involve early and timely the local community;
2) Start the planning of the NDP as soon as possible, and even better when the facility is still operating; and
3) Privilege the siting of a waste repository where a nuclear licence has been already provided.

These are the NDPs’ promoting factors from the social and ethical perspective.

These three factors, can be generalized to non-nuclear industrial sectors entering the decommissioning stage, as it is essential to supply to the employees, the local community and their political representatives prompt, with accurate and reliable information. In addition, it is pivotal to provide stakeholders with ancillary support (both in the form of economic compensation and psychological help), and to make sure that the number of employees needed to accomplish the decommissioning project reduces together with the increase of people who retire.

Strictly related to the early engagement of stakeholders, is also the early start of planning a decommissioning project: early planning promote a gradual change of culture within the company and reduce the impact of the transition between operation and decommissioning.

Lastly, the use of an already licenced site to locate the waste repository or a landfill is likely to be better accepted by the community. This is particularly relevant for the nuclear industry where the waste produced can be only partially recycled, but it is also relevant for other decommissioning projects, where the early selection of where to place the waste generated during the decommissioning activities can reduce future costs.

In conclusion, along with NDPs, also the decommissioning of Oil&Gas, dams and mines accounts for a budget in the range of thousands of billions. To this extremely high budget are associated an even higher social responsibility: project management, traditionally focused on construction, needs to learn as soon as possible how to manage decommissioning projects in a socially-responsible way, focusing also on future generations.

Conflicts of interest

There is no conflict of interest.

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Appendix A

Table 3
Social challenges of decommissioning projects.

NDP	Name and country	Social challenge analysed and its consequesnces	Stakeholder reaction
Transition from operation to decommissioning	**Kozloduy — 1 & 2, Bulgaria**	Kozloduy NPP, Bulgaria, is one example where the shutdown of the facility caused an abrupt reduction in personnel, and led to a decline in motivation due to frustration, fear of change and a loss of confidence in management. To tackle this issue, a training centre for the employees was established, but more absenteeism and increase in stress is still highlighted (IAEA, 2008b). Since Kozloduy NPP was affected by early closure and it is a heavy financial burden for these countries, the EU provided financial support (Öko-Institut, 2013; IAEA, 2009).	**Disputed NDP**
	Ignalina — 1 & 2, Lithuania	Ignalina NPP, Lithuania, is an example of a socially and geographically isolated NPP. Its closest town, Visaginas, has been hardly hit by the closure of Ignalina NPP, and has suffered not only by the decline in staffing and prestige of its largest employer and the loss of the original reason for the town's existence, but also from a near 5-fold rise in heating prices (Ministry of Energy, 2011). The European Union has accepted to bear the economic and social impact of Ignalina NPP closure (IAEA, 2009), (Öko-Institut, 2013) , because without sufficient funding, the whole decommissioning process will require even greater financial resources, staff expertise is likely to be lost and social tensions will exacerbate in the region.	**Disputed NDP**
	Superphénix, France	At Superphénix, France, the relocation process progressed easily at the beginning, but it became more difficult with each passing year. This last period of staff reduction (2003–2004) was a difficult one, as most people did not want to relocate, there was lack of motivationamong personnel, it was too early to recruit new young people (IAEA, 2008b).	**Disputed NDP**
	Greifswald — 8 units, Germany	At Greifswald, Germany, activities such as re-training for some employees, education for new jobs for and the adoption of retirement scheme have been undertaken, together with a scoring system has been adopted to categorize employees and decide who to re-train and who to re-deploy (Backer, 2012b; IAEA, 2008b). However, there was a the decrease of working moral and productivity, Increase of unemployment, decrease of tax yields and less opportunities for investments, and one of the substantial problem was ensuring the acceptance of the public (Backer, 2012b). Also, of the staff that was working in Greifswald, one third needed to get a new job, and one third remained either jobless or retired (Backer, 2012b). Additionally, the IAEA highlights that the shutdown caused a degree of local uncertainty (IAEA, 2008b).	**Disputed NDP**

Table 3 (*continued*)

NDP	Name and country	Social challenge analysed and its consequesnces	Stakeholder reaction
Transition from operation to decommissioning	**Vandellós-I, Spain**	At Vandellós-I, Spain, the ENRESA mitigated the negative socio-economic impact of the NPP shutdown hiring local and provincial companies (65% of the employees) and implementing a complete training plan to provide the workers the necessary knowledge (NEA/RWM/WPDD, 2007; ENRESA, 2007). Here, employment was perceived to be the main local concern, especially as staff numbers have dropped from 350 when the plant was operational to about 100, and would have reduced to 50 during the latency period (Bond et al., 2004).	**Accepted NDP**
	Barsebäck, Sweden	The Barsebäck NPP, in Sweden, is a meaningful example of positive outcome of a sensible management of staff to maintain the feeling of personnel security: this was achieved, for example, through 3 to 5 years of employment guarantee before the reactor was closed and several initiatives, such as individual supportive discussion (Lorentz, 2009; IAEA, 2008b).	**Accepted NDP**
	José Cabrera, Spain	José Cabrera, Spain, is an example of early and timely stakeholder involvement, that promoted the successful progress of the NDP (IAEA, 2016a).	**Accepted NDP**
	Trawsfynydd, UK	In Trawsfynydd, UK, the consultation strategy started with the identification of three groups on whom the decommissioning was likely to have a socio-economic adn environmental impact, i.e. (1) employees, (2) people living within 25–30 km radium from the nuclear site, (3) locally elected council. In fact, even if social groups within communities have different priorities (Whitton et al., 2015), the Trawsfynydd staff management proved to be efficient, with 75–85% of people allocated to their first choice, and only a very small number of employees who defined themselves as "*significantly dissatisfied*" of their final allocation and of the management approach (Jones, 1993). NDA's stakeholder consultation (NDA, 2009) also shows the NDA ongoing commitment towards the stakeholder (Bond et al., 2004).	**Accepted NDP**
Search for the siting of a nuclear waste repository	**Scanzano Jonico, Italy**	Scanzano Jonico, Italy, was chosen as a nuclear waste repository to unlock a ten-year temporary situation in the management of radioactive waste (IAEA, 2009). This waste was a legacy of the work done by the first Italian nuclear power plants (turned off after the referendum of 1987) and from the routine activities of research centres and hospital. However, the communication to the population regarding the site selection came completely unexpected (through Decree Lawn.314 of 14 November 2003) and the citizens of Scanzano Jonico were totally unprepared and uninformed of the topic. This caused the rise of critics and protests form the local community that lasted several days (Bentivenga et al., 2004; Zinn, 2007). The arisen protests caused not only a delay in the project, but also the total removal of the assignment to Scanzano Jonico and the withdrawal of the whole project.	**Disputed AND abandoned NDP**
	Onkalo, Finland	Onkalo, Finland, is an extremely good example of successful search for the repository of spent nuclear fuel and nuclear waste where a repository which is currently under construction at the Olkiluoto NPP site in Finland. Due to the Finnish open and transparent policy and the overall trust in the public authorities, no major protests of the local community have arisen (EU Committee, 2006): in May 1991 the government approved plans for a geologic repository, and after twenty years of consultation and research investigation the repository is to be sited at Olkiluoto (EU Committee, 2006); in February 2015 the regulators approved the waste repository plan (WNN, 2015a), and the construction licence was granted in November 2015 (WNN, 2015b).	**Accepted NDP**

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Publication III

“Characterising nuclear decommissioning projects: An exploration of the end-of-life of nuclear infrastructure”

Characterising Nuclear Decommissioning Projects: an Investigation of the Project Characteristics that Affect the Project Performance

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Abstract

Historically, project management research on infrastructure has mostly focused on its planning, design and construction. However, globally, more and more infrastructure, such as nuclear power plants, bridges, dams or oil rigs, are reaching their end-of-life and will soon need to be decommissioned. Decommissioning projects are long, complex and range from small projects to multi-billion megaprojects. Moreover, their costs keep increasing, while there is a limited understanding of why this happens. This paper aims to collect and analyse the characteristics of decommissioning projects that affect their cost and time performance. Nuclear Decommissioning Projects and Programmes (NDPs) are used as unit of analysis due to the relevance of this sector and the number of public information available. Findings from the application of content analysis on interviews with senior practitioners highlight the importance of several NDP characteristics, including the need to have good knowledge of the site conditions, good relationship with the regulatory authorities, the availability of storage facilities and of stable funding. Lastly, this paper discusses the need to investigate transferrable learnings across sectors.

Keywords

Decommissioning; Engineering and Management; Infrastructure; Project characteristics; Nuclear.

1 The Need of Project Management Research in Decommissioning

By far, the project management research on success and failure of projects has focused on the planning and construction of infrastructure, and until now, only limited attention has been put on its decommissioning. Decommissioning refers to the process of withdrawing an infrastructure from service, taking it apart and deconstructing it. Specifically when referred to nuclear, decommissioning is defined as all the administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility (IAEA 2006a). For some industrial sectors (such as nuclear), decommissioning involves also the construction of new facilities, e.g. to treat and store the waste material that arise during de-construction. In other words, decommissioning includes construction work as well.

Decommissioning is a new, emerging, global challenge that project practitioners and academics need to understand and tackle. Indeed, in the project management literature, the "success" of construction projects has been extensively investigated (see for example the literature review by Ahola & Davies (2017)). Also, the evaluation of project success has evolved from the "iron triangle" of time, cost and quality, to include a broader set of criteria, including both objective and more subjective ones (Williams 2016). Conversely, the review of the literature revealed that there is very limited research on "success factors" in decommissioning[1].

This limited project management research dealing with decommissioning is at least partially due to the fact that infrastructure that has been built throughout history is substantially more than the number of completed decommissioning projects. Indeed, while the construction of

[1] This is exemplified by the search in Scopus of the keywords "project management", "success", "factors", "construction", which highlights 738 publications (Exact queries in Scopus (as in February 2019): "project management" AND "success" AND "factors" AND "construction") Conversely, referring to decommissioning, the search in Scopus reveals only eight publications (Exact queries in Scopus (as in February 2019): "project management" AND "success" AND "factors" AND "decommissioning"), most of which are conference proceedings. Moreover, the broader search in Scopus of the keywords "project management" and "decommissioning" (Exact queries in Scopus (as in February 2019): "project management" AND "decommissioning") reveals 348 publications, only two of which published in the International Journal of Project Management, i.e. (Invernizzi et al. 2017b; Invernizzi et al. 2019a), none in the Project Management Journal and none in Construction Management and Economics.

infrastructure, even complex and large ones (like the Pyramids, the Colosseum and the China wall) started thousands of years ago, the decommissioning of infrastructure (such as nuclear and oil & gas facilities) has been emerging (and is rapidly growing) only since the last decades. However, more and more infrastructure needs to be decommissioned for several interrelated reasons, embracing safety, security, ethical, moral and regulatory-related ones, and are raising more and more techno-socio-economic challenges.

Consequently, while far more experience has been accumulated in the construction sector, both by practitioners and academics (Williams 2016; Zavadskas et al. 2013; Lam et al. 2008), decommissioning projects urgently necessitate more attention and management research.

Decommissioning projects are complex, long and expensive, and range from small projects to multi-billion megaprojects. For instance, the decommissioning of the UK Continental Shelf reach a staggering £60bn (Oil & Gas Authority 2017), while the decommissioning cost estimates of the UK nuclear legacy alone currently reach £229 billion (NDA 2019), a remarkable increase compared to the first estimates published, which reached £24 billion (NDA 2006). In fact, several of the cost estimates of these decommissioning projects keep increasing, and there is there is a limited understanding of why this happens.

This paper focuses on Nuclear Decommissioning Projects and Programmes (NDPs), intended as site-level endeavours, primarily due to the economic relevance of this sector, and the number of publically available information. More specifically, this research is restricted to the analysis of commercial European NDPs, primarily because of the greater homogeneity in regulations and the availability of information.

More specifically, this paper addresses the following research question:

- Which NDP characteristics affect the difference between time and cost estimates of NDPs and the NDPs' actual time and costs?

This is a key difference compared to most of the literature (see section 2.2) which deal with cost estimates of NDPs (e.g. (Torp & Klakegg 2016; OECD/NEA 2010)).

Also unlike the more traditional project management research on "success", this paper uses the terms "characteristics" and "performance" in place of the more common "success factors" and "success criteria", mainly due to the exploratory nature of this research and the fact that the authors do not want to give neither a positive nor a negative connotation to a list of characteristics that affect the project performance (as in principle they can be both positive negative or neutral, so naming them "success factors" could be misleading).

The rest of the paper is structured as follows: section 2 introduces the research background, illustrating the dearth of project management literature on decommissioning projects. Then, section 3 describes the research method, focusing on the description of the collection of primary data and information and their analysis. Section 4 illustrates the research findings, while section 5 discusses these findings in light of the existing literature. Section 6 presents the limitations of the current research and suggests future research path. Section 7 concludes the paper.

2 Research Background

This section is divided into two subsections. The first subsection briefly discusses the studies on the factors that affect the project performance, focusing on the literature on “success factors” with a focus on construction of infrastructure due to its dichotomy with the decommissioning and the volume of research on this topic. The second subsection explains the project context of decommissioning projects, and particularly NDPs.

2.1 The Vast Project Management Research on Success Factors

Project management research dealing with the success and failure of projects is extensive and keeps providing fertile ground for research, so much that Turner et al. (2013) define one of the “project management school of thought”, the “success school” (Turner et al. 2013, p.17-18).

There have been different periods in studying project success factors, each widening the definition of success ((Turner & Müller 2005, p.56), quoting (Judgev & Müller 2005)). Providing one of the earliest literature review on “success/fail factors”, Belassi & Tukel (1996), explained that success and failure factors were first introduced in the late ‘60s, when technical performance was used as a measure for success (Belassi & Tukel 1996, p.142). In the ‘70s, project success focused on implementation, measuring time, cost and functionality improvements, and systems for their delivery. From the ‘80s and ‘90s, lists of critical success factors started to become more popular, and more dimensions were included in the investigation of projects success, e.g. related to the project context (Turner & Müller 2005). Pinto, Slevin and Prescott gained great popularity due to the broad and systemic approach that they took (Müller & Jugdev 2015, p.759). Their research was then followed by several publications discussing project success factors and criteria and embracing several different topics, including project managers and project management (Müller & Turner 2007; Mir & Pinnington 2014; de Carvalho et al. 2015), project governance (Joslin & Müller 2016), knowledge management (Jennex 2006), etc.

Focusing specifically on the construction industry (pertinent for this research due to the dichotomy construction/decommissioning and as a well-investigated research context), several studies have focused on "project success" and investigated what affect this success. For example, focusing on construction, Chan & Chan (2004) discussed the different dimension of project success, developing a framework for measuring the success of construction projects. Bing et al. (2005) investigated what affects the success of public-private partnerships in the UK construction industry. Faridi & El-Sayegh (2006, p.1167) researched on the "*most significant causes of delay*" in the UAE construction industry. Chen et al. (2012) reviewed the literature on critical success factors, and discuss the interrelationships among critical success factors of construction projects. Lindhart & Larsen (2016) extracted the top 5 success factor and failure factors from a list of selected publications, concluding that knowledge sharing and communication are key to improve cost, time, and quality performance. Williams (2016) showed how success factors combine in complex interactions, investigating the root causes of these success factors. More recently, Tripathi & Jha (2018) provided a summary of the literature review on "success/failure factors" of construction organizations testing what they called "success attributes" against their "performance attribute" through structural equation modelling. Olawale & Sun (2010) shifted the focus on the factors that inhibit the ability to control projects, also developing suggestions to address the most inhibiting factors, i.e. "*design changes, risks/uncertainties, inaccurate evaluation of project time/duration, complexities and non-performance of subcontractors*".

Focusing specifically on nuclear construction, Grubler (2010) emphasises that the reasons for the successful French nuclear program included its institutional setting, which allows central decision making, regulatory stability, and the use of standardized reactor designs. Berthélemy & Escobar (2015) argue that the variety of models of reactors under-construction and their increase in size contribute indirectly to costs escalation through increasing their construction times, while there are positive learning effects when the same models are built by the same firm. Moreover, these authors suggest that innovation might contribute to the cost increase. Locatelli (2018) reviews the key aspect for the successful planning and delivery of a nuclear programme, concluding that the standardisation of the design and supply chain availability are essential.

Far from being exhaustive, the above-mentioned literature on project success factors offers one key message: the project management literature investigating project characteristics and project performance (respectively often called success factors and measured through specific success criteria) is vast and wide-ranging. Conversely, there is a gap in knowledge about the characteristics of decommissioning projects that affect their performance. However, there is a growing urgency to investigate decommissioning projects (and NDPs in particular), due to the fast-growing array of infrastructure that is approaching its end-of-life, and the costs (economic, social and environmental) that its decommissioning will involve.

2.2 The Limited Research on Decommissioning Projects

Decommissioning projects are the new, emerging, global, unavoidable challenge that project managers and policymakers will face more and more severely in the future. Regarding the US hydroelectric sector, Oldham (2009) reports that in the US there are 79,000 "significant dams" but that only 600 (mainly small ones) have been partially or completely removed in the twentieth century. Also in Europe, several dams will need to be decommissioned soon (e.g. see (leNews 2017) about decommissioning in the Alps).

The oil & gas industry is currently facing increasingly relevant challenges, as according to Parente et al. (2006), the number of petroleum installations in the world exceeds 7,500 units. The US case is dominated by the decommissioning and dismantling of the offshore installations in the Gulf of Mexico, where approximately 4,000 structures used to produce oil and natural gas (Kaiser 2006) and whose costs are estimated to reach several USD billion by 2040 (IHS Markit 2017). Europe is not exempt from these concerns and, according to the UK House of Commons (2017), the scale of decommissioning the UK oil & gas Continental Shelf which comprises thousands of wells to plug and abandon, as well as hundreds of other subsea platform and floating installations to decommission. Additionally, discussion dealing with the end-of-life of low carbon infrastructure, such as photovoltaic panels and wind farms has also started to emerge (Cartelle Barros et al. 2017; Topham & McMillan 2017).

Decommissioning projects are often at least partially commissioned by the Government, involve a considerable number of stakeholders both contractually related to the project and not (e.g. like the local community surrounding the project), and shape and are shaped by the environmental and social context in which they are developed.

Among other decommissioning projects, NDPs are among the most challenging ones because of:

- Technical and regulatory-related challenges, which arise due to the management of radioactive and highly toxic material arising from decommissioning and the high volumes to be lifted and transported (Steiner 2012; Valencia 2012);
- Economic and financial challenges, which arise as decommissioning costs are in order of billions and keep increasing, while often insufficient or inexistent provisions were reserved for decommissioning and waste management (LaGuardia & Murphy 2012);
- Social and ethical challenges, including personnel transition and public unacceptance (Invernizzi et al. 2017b)), as well as considering a broader range of external stakeholders, such as current and future generations that have to bear the cost of decommissioning (as most of decommissioning in Europe is funded with tax payers' money), while the benefits provided by the infrastructure were exploited by past generations (Taebi et al. 2012);

- Environmental challenges, which arise in the attempt to restore the site to its previous condition (Fellingham 2012).

Remarkably, even though NDPs are such important projects, only very recently has the analysis of NDP characteristics that affect the NDP cost and time performance from the project management perspective started to attract the attention of the academics and practitioners. For example, Studsvik et al. (2016) illustrate the importance to plan decommissioning and waste management, as well as to identify and mitigate bottleneck, avoid sub-optimization and minimize waste amount for disposal. Sykora et al. (2016) underline the importance of early preparation for decommissioning and highlight the importance to:

- build a decommissioning team composed of both plant staff and specialists;
- insist on pre-work and on a thorough radiological characterization[2];
- develop a tailored "decommissioning manual";
- replace the plant's legacy support systems with modular systems fit for decommissioning.

Kim & Mcgrath (2013), basing their analysis of eight US NDPs, investigate the components of decommissioning costs, and highlight that costs do not generally trend with plant generating capacity and size. Moreover, they highlight how among other decommissioning cost categories, "staffing costs" represents the highest percentage, followed by "removal costs" and "waste costs".

More recently, reports published by international organizations publications on decommissioning have increased in number and quality, and include reports by the International Atomic Energy Agency (IAEA/OCED-NEA 2017; IAEA 2011; IAEA 2016b), the OECD/Nuclear Energy Agency (NEA) (OECD/NEA 2016; OECD/NEA 2015;

[2] Where characterization refers to the determination of the nature and activity of atoms that undergo radioactive decay that are present in a specified place (IAEA 2006, p.18)

OECD/NEA 2012), the European Commission (EC 2018), the European Court of Auditors reports (2016; 2011) and others (e.g.(Öko-Institut 2013; Laraia 2012a; Wuppertal Institute 2007b)). However, these publications do not systematically collect and analyse the NDP characteristics that affect the difference between time and cost estimates and the actual time and costs. More specifically, the above-mentioned publications tend to focus mostly on NDPs cost estimates (e.g.(IAEA/OCED-NEA 2017; OECD/NEA 2012; OECD/NEA 2010)), discuss costs but not time performance (e.g. (OECD/NEA 2016)), focus on a small number of European NDPs (European Court of Auditors 2016; Öko-Institut 2013), or provide the perspective of single experts on single topics, respectively authors of different chapters of (Laraia 2012a). However, a European-wide study on the NDP characteristics that affected the NDP performance is still missing. This research addresses this gap in knowledge, and the above-mentioned practitioners-based publications consist of the most relevant source of information to understand the research context.

3 Method

The research method needs to deal with a number challenges: first of all, at a global level, there are very few NDPs, as, for instance, only 16 of the nearly 150 civil nuclear power reactors that have ceased operation have undergone complete decommissioning (OECD/NEA 2016, p.3). Moreover, public information on completed or ongoing NDPs is extremely limited and unstructured, and reporting procedures are hardly comparable in different countries. These data and information available consists of a mix of quantitative and qualitative data, usually the latter being more comprehensive and exhaustive than the first. This makes it difficult to systematically analyse the collected information, as quantitative analyses alone are not suitable for researching NDPs.

This research is based on primary data collected during interviews with senior practitioners, which were analysed through content analysis.

Interviews based on a questionnaire built for this research

Interviews with senior practitioners were selected to collect primary data because of the richness of the information they provide. Interviews were based on a questionnaire that was used as a basis for the conversation. The questionnaire was sent to the respondents at the same time of the invitation to participate to the research and contained both open and closed questions. The first open question was very broad and anticipated all the others and read as follows: "*In your opinion, which NDP characteristics mostly impact on the NDP performance in term of cost and time*?". This first question was asked to let the tacit knowledge of practitioners emerge (Addis 2016), without suggesting any preconceived answer. Additionally, as in other comparable studies such as (Ahiaga-dagbui et al. 2017), the author used personal judgment to ask follow-up this question to clarify the interviewees' comments.

The primary data and information analysed in this paper referred only to the discussion triggered by this first question. The relationship between the answers of the closed questions and the NDP cost performance was statistically tested elsewhere (Invernizzi et al. 2019a).

Selection of the interviewees

The interviewees were selected through purposive sampling (Palinkas et al. 2015), primarily according to their involvement on at least one of the NDP shown in Table 1, which list 29 ongoing European NDP, where the information on the evolution of the estimate at completion is publically available from reliable sources[3]. Moreover, NDP senior practitioners from Sweden, Finland, Switzerland and the Netherlands (which are countries with nuclear power plants) were also involved in the research. The interviewees were also selected according to their seniority and their role in the organization. The interviewer (i.e. one of the authors) sent 75 emails to invite the senior practitioners involved in decommissioning project across Europe to participate to this research. Ultimately, 35 interviews were conducted, for a rate of response of 46.7%. In total, 82 % of the interviewees had more than 10 years in the industry, and interviewees included senior project and programme managers, programme enablers, head of projects, project leaders, managing directors, one head of international development, and one senior auditor of the European Court of Auditors. The interviewees covered the following countries: UK, France, Italy, Spain, Germany, Lithuania, Bulgaria, Slovakia, Sweden, Finland, Switzerland and the Netherlands.

[3] Information about NDP time performance are unfortunately virtually absent and not even international publication that discuss NDP cost (e.g.(OECD/NEA 2016)) provide information about NDP schedule. One rare exception is the UK case (NEI 2017). Sellafield NDP is not included in this analysis as it stands out as a complete outlier, with Sellafield's decommissioning estimates accounting for more than 70% than the UK overall estimates.

Description of the interview process

The interviewees were not required to answer any of the questions in a written form, but they were given the possibility to read the questions in advance. In this way, the interviewees were given time to decide if they wanted to participate to the study or not. Of the 35 respondents, three preferred to email the completed questionnaire before the oral conversation, and in two of these cases, a follow-up conversation was arranged to comment on the answers orally. Two conversations took place in person, while the remaining conversations took place via phone or Skype. The interviewer (one of the authors) is fluent in 3 languages: English, French and Italian, so the interviewees were given the possibility to choose one of these languages. Ultimately, two interviews were performed in French, four interviews in Italian, and the rest in English. All the interviewees were granted anonymization. When permission for recording was granted, the interviews were recorded, and the conversation was transcribed. Extensive notes were also taken by the interviewee during the interviews, which resulted important especially when the permission to record was not granted by the interviewee (only one case). The overall interviews were forecast to last 30 to 40 minutes, but eight interviews lasted more than one hour, which was due to the eagerness of some of the interviewees to provide more detailed answers. The average duration of the interviews was 45 minutes.

Analysis of the interview

All the interviews were thoroughly transcribed by the interviewer (i.e. one of the authors). Transcriptions are theoretical constructs and not necessarily “holistic” representations of data and that there is a need to reconcile “how” data are constructed with “what” topics are being discussed (Roulston 2010). This is addressed in an initial systematic categorization of the information provided by the interviewees in NVIVO11, a data analysis software that supports qualitative and mixed methods research. The initial categorization was then refined in several iterations to finalize the coding for the data analysis (as described below), on the basis of (Olawale & Sun 2015; DeCuir-gu & Mcculloch 2011; Elo & Kyngäs 2008), and following the recommendations for the preparation and analysis of data by (Mclellan-Lemal & Macqueen 2003; DiCicco-Bloom & Crabtree 2006). Ultimately, the transcribed material was systematically analysed using content analysis (Dixon-Woods et al. 2005; Kohlbacher 2006), and more precisely directed content analysis (Hsieh & Shannon 2005).

4 Research Findings

In several nuclear sites, nuclear material and waste have accumulated over the years. Moreover, since particularly in the 50s and 60s the record keeping was poor (or records have been lost), it is now often unclear exactly how much waste and which type of waste is on site. Indeed, there thousand (or more) different types of "nuclear waste" and almost each of these types need to be treated and stored in a different way. For some waste (the most common in volume and type), there are clear and established treatment procedures, while for other types of waste (that could even be unique to one site), the procedures to treat and store this waste can still be in the R&D phase or not available at all yet.

Waste from a nuclear site can include soil where radioactive liquid has been leaked, buildings that have been storing nuclear material for decades and whose access is limited due the lack of knowledge of the content of this nuclear material, sections of power plants that are difficult to inspect, or even ponds or wells where different types of radioactive waste have been left for several years.

So, assuming, for example, that the project scope is to clean up the site to a greenfield status, the key issue is that the starting point of the NDP is not clear (in terms of the exact amount and type of waste on site) and therefore how to get to the end point is complex to define (i.e. how to handle the waste). For these reasons, a fundamental point for NDP is the "characterisation" of the site, i.e. understanding which type of waste is on site. More formally, characterisation in the nuclear industry refers to the determination of the nature and activity of atoms that undergo radioactive decay that are present in a specified place (IAEA 2006, p.18). Characterization is the way to address, at least partially, the unknowns about the site-condition of the NDPs. The following sections summarised in a structured way the main findings.

Unknowns and uncertainties about the site condition

The first interesting NDP characteristic that was highlighted by the interviewees is related to the “unknowns and uncertainties” about the site conditions, which triggers the need of (additional) characterization.

These "unknowns and uncertainties" are caused by the fact that the nuclear facilities undergoing decommissioning have normally been built decades earlier, and both during their construction and operational history, they might have been affected by structural modifications or changes, or might have suffered leakages or spilling of radioactive material that has not been systematically recorded. Hence, additional characterization to increase the knowledge of the site condition emerges to be necessary during the NDP progress, and this delays the overall NDP and increases its costs.

On this matter, one interviewee explained: ”…*which are the characteristics that impact on the NDP the most? First of all (and it should not be a surprise for you!), characterization and knowledge of the initial status. Ok? If you are not aware of this, it is going to be a trouble! And you should have the description of the facility as built and not as designed. Or you should have both actually, but as built is crucial"*. Another interviewee stressed: “*The majority of uncertainties are related to the quantity, topology and activity of the nuclear material in the plant! And we need to know the plant, before decommissioning it”*.

Moreover, not only unknowns and uncertainty are related to nuclear material but also, for example, to asbestos (which was explicitly mentioned by some interviewees as an issue for NDPs). Asbestos is the name of a family of naturally occurring minerals, and becomes a concern when fibres are present in air, because people can inhale them, and this can cause asbestosis, lung cancer, mesothelioma and other cancers (IAEA, 2006c, p.38-40). One interviewee explained: "*most instances that results into additional scope when we come in...we may find asbestos that we haven’t foreseen being in an area of the site!*”.

Limited clarity of the waste routes and availability of storage and disposal facilities

The above-mentioned concerns related to the uncertainties of exact type and quantity of waste material on site are strictly connected to the second most-emphasised NDP characteristic that affect the NDP performance, which refers to the clarity of the waste routes and the availability of storage and disposal facilities. During the lifetime of a nuclear facility, nuclear waste of very different nature is created. This waste can derive from the operations of a nuclear reactor, and includes the spent fuel from the refueling operations of a nuclear reactor (which is highly radioactive), or the gloves and suits used daily by operators in particular areas of a nuclear facility (which are considerably less radioactive). Moreover, it might derive from research experiments (and therefore most likely be in very small quantity but unique in its physical properties), or from the scabbling of a thin layer of concrete from buildings wall to remove surface contamination (and therefore creating large volume of waste with similar physical characteristics), or other activities. All these different types of waste (and many others) need to be converted into a solid form that is resistant to leaching, and is suitable for transportation, short-term storage, and ultimately disposal (WNA 2019). Hence, each type of waste require a different "waste route", and if these "waste routes" are not clear, the NDP performance are affected.

On this topic, the following comment is exemplary: "*Understanding the waste routes is fundamental. If you don't get that right, it's a waste of time. You need the right planning, and using the waste hierarchy. If you don't have that in place, nothing else can work. The interface between how radioactive waste management team and the decommissioning teamwork is designed is fundamental. If you cannot handle properly the waste in a facility, all the waste gets constipated, and almost causes issues with the regulators, because the regulators say 'you're generating waste, but you actually don't know where to put it'. It's not good if you cannot 'demonstrate' the waste routes…"*.

Regulatory-related challenges

The last interviewee's comment also introduced another NDP characteristic repeatedly stressed by the interviewees, which consists of regulatory-related challenges. In the nuclear field, safety and environment are dealt by a different regulatory bodies, such as the Office of Nuclear Regulation and the Environment Agency in the UK.

The interviewees highlighted regulatory-related challenges both concerning the relationships with regulatory bodies, as well as the strictness of regulations and the effect of their changes.

Concerning the relationship with the regulatory bodies, one interviewee explained: *"Good relationships with the regulatory body ... a relationship of, we could say, continuous "exchange" with the regulatory body [is important]. And then, concerning the relationship with the regulator, I would not only say the exchange of information, monthly or weekly, but also the presence of the regulatory body on the site, which we unfortunately do not have… [is important*]".

Conversely, concerning the changes in regulations, one interviewee stated: *"In 2016, a law came out, the one that defines LLW and ILW in Italy. First we had an old law ... […]. And, for example, there is a new obligation on nickel. That nickel is a big problem for us… because we had to review the classification of some waste that has passed from LLW to ILW!".* LLW stands for Low Level Waste and ILW stands for Intermediate Level Waste. Since ILW is waste that is more radioactive than LLW, it requires more stringent treatment, shielding, and storage than LLW, and its cost is considerably higher than the cost of LLW. If additional funding to deal with these changes is not ready available, the overall NDP performance might be affected.

Stable funding, Government ownership and contractual agreements

On the top of the abovementioned characteristics, the interviewees highlighted the availability of stable funding and Government ownership of the NDP. These are related to each other, as the fact that the NDP is owned by the Government is, at least to a certain extent, a "guarantee" of stable funding. However, it might also be the cause of delays, as the end of the NDP would coincide with the termination of the employees' job, which they would not want to accelerate. Indeed, one interviewee explained: "*The problem is that the projects are in the hand of a public entity, the Government, and that's ok because it gives us guarantees, the problem is figuring out how to speed up this stuffs ... It's unbearable that this [decommissioning] lasts sooo long!".* The latter NDP characteristics is also related to the challenges with procurement and contractual agreements. For example, one interviewee explains: "*As such [public company], we must comply with the European directive on the procurement of contracts and thus the process of competition is relatively confused. We must be able to demonstrate that there is no discrimination […]. And so the associated process is relatively heavy, it is necessary to publish notices of market, it has published criteria quite precise […]. So takes a long time, and the best-known company is not always the best for the project".* Similarly, another interviewee emphasised "*As a public body, we are subject to public procurement procedures and those can also take decades and I am not saying a random number because I have in mind a race that has been going on for more than five years".*

The need of early planning

Early and detailed planning was also mentioned several times as a relevant NDP characteristic that affect the NDP time and cost performance. One interviewee said: *"Planning! Planning! Planning! The most important thing! […] to organize the work and different alternatives routes and so on!".* Another explained: *"This [plan] is the most important part that we have done in this industry! It's a plan that goes from cradle to grave! From the start to the contract, to the end of the contract, until complete decommissioning, we know exactly what we want: it is planned to be done! We can track it against the overtime, in terms of cost and schedule!"*

The availability of suitably qualified resources

The availability of suitably qualified resources and the reliability of the supply chain also stressed repeatedly by the interviewees. One interviewee explained: *"One of the other problems, or characteristics, I think, is getting the right resources, getting the right people in place. Many many of our projects that you look at, you'll notice that there is a key resource missing!".*

Limited clarity of the final end-state

Furthermore, several interviewees highlighted their concerns about the lack of clarity of the site end-state and consequent limited scope definition of the NDP. The end-state of a NDP is normally either to restore the greenfield status, i.e. bringing the site to the condition it was before the nuclear facility was installed, or to reach a status in which the site could be reused for future industrial purpose (e.g. a new nuclear installation). Comments on the lack of clarity of the end-state were also sometimes ascribed to changes in the overall national strategy. Limited clarity of the end state hinders the progress of the NDP, and as one interviewee explained: "*it is really important that this is clear! […] getting a better definition for the different phases. So, what is 'Care & Maintenance' going to look like, what is final state going to look like. And I think you want to put more thoughts in site clearance…but those seem so far away".*

Social-related challenges and knowledge management

The limited agreement on the final site end-state and the numerous discussions regarding the best way forward might be one of many triggers of social-related challenges. Social-related challenges include public unacceptance, as one interviewee explained: "*the populations that* *does not want [decommissioning]",* and personnel transition, as another interviewee explained*: "they had to start to re-build the organization that was there to decommissioning and maybe they were downsizing too far too fast, without thinking through which skills and expertize was better to maintain".*

The latter interviewee also explained that the downsizing in the transition from operations to decommissioning being too fast, caused a loss of knowledge of the nuclear facility, and triggered the need to re-employ ex-operators. This comment introduces another NDP characteristics that was stressed by the interviewees as one NDP characteristic affecting the performance of NDPs, which consists of knowledge and information management. Knowledge and information management were explicitly stressed by four interviewees as affecting the NDP performance. Knowledge management refers to "*the deliberate design of processes, tools, structures, etc., meant to increase, renew, share, or improve the use of knowledge represented in any of the structural, human and social elements of intellectual capital'* ((Kaivo-oja 2012) quoting (Giland 2004)). Information management refers mainly to managing the data that are created on a daily basis, how they are stored, retrieved and shared. These are challenges for NDPs, and interviewees explained that *"knowledge management is a big issue, people are getting older and the handover is weak*" and that "*people that were working are retired by now. And we have less and less access to historical information from the* past and from operations".

More tentative propositions

Additionally, the following comments have been mentioned by the interviewees.

First of all, two interviewees mentioned the lack of project management experience, one of them expressing his frustration, by stating that one of the most important NDP characteristic is "*the capability of actually executing the plan and sticking to it. So [...]: the management of the project, the project leader and the management team and the quality of their work is very* *important to the result*". In addition, two interviewees highlighted the (high) personnel costs. Two others stressed the complexity of the governance as affecting the NDP performance, where "governance" is intended here as involving "*a set of relationships between the project's management, its sponsor (or executive board), its owner, and other stakeholders*" (Turner, 2009, p.312).

Finally, the following comments were highlighted in different interviews. These consist of:

- The design of the nuclear facility, completed with no thought about decommissioning in mind (so, for example, several parts of the facility that need to be decontaminated are hard to reach), which hinders the decommissioning of the nuclear facility;
- NDPs being "first of a kind", i.e. projects that cannot rely on previous experience, due to the high variety of designs, the different purposes that the nuclear facilities served, their unique operational history, and the very small number of completed NDPs.
- Over-engineering of solutions, which affect not only NDPs but also the overall nuclear industry causing cost-overruns;
- The importance of incentives schemes, to promote work adhering to strict deadlines.
- The adoption of a "program-based" approach across the country, i.e. the management of NDPs in different locations to promote the sharing of lessons learned across NDPs;
- The exploitation of pilot projects and mock-ups, i.e. the testing and training of an activity off-site before it is performed on-site, which facilitate the training of the employees before entering the nuclear site, which ultimately reduces the costs of on-site operations, as they can be completed more effectively;

The benefits of using a "program-based" approach was highlighted by one interviewee from the UK, who stated: "*There was a 'programmized' approach that every kind of site adopted and actually is greatly received […]. A project that I worked for, the waste programme, we are already anticipating some significant savings as a result of adopting generic design for similar* *projects across the program. So for example: waste retrievals, ILW retrievals. There are multiple sites across the portfolio that require certain retrieval system!"*. This programme-based approach can be adopted especially by other countries where several NDPs are owned or managed by the same organization (e.g. in France), and can promote the sharing of lessons learned from one site to the others, and ultimately improve the NDP performance.

The impact of pilot projects and/or mock-ups, was also explained to be valuable in the nuclear industry, because, due to the presence of radioactive material, the activities performed within the perimeter of a nuclear-licenced site are considerably more expensive. One interviewee explained: "*we have a facility, a non-active facility…[…]. We can re-create some parts and we can do inactive tests on this and we actually do train the operators to do all the operations that are gonna be tricky within the plant!"*.

5 Discussion

The previous section addressed the research question of this paper:

- Which NDP characteristics affect the difference between time and cost estimates of NDPs and the NDPs' actual time and costs?

Due to the exploratory nature of this research, circumspection in answering the abovementioned research questions is fundamental, and the number of interviewees that mentioned a NDP characteristic should not be taken as a proxy for its impact on the NDP performance, but simply as an indication of their relevance according to the interviewees.

The most quoted NDP characteristics

Among the NDP characteristics presented in section 4, "unknowns and uncertainties about the site condition, and the need of (additional) characterization" is the one that has been mostly stressed by the interviewees. This finding is reflected for example by the following statement from the UK Government website, which refers to UK NDPs, and states: *"in recognition of this uncertainty, the NDA [Nuclear Decommissioning Authority] publishes a range of estimates that could potentially be realistic. Based on the best data now available, different assumptions could produce figures somewhere between £99 billion and £225 billion"* (NDA 2019). *"Unknowns" and "uncertainties"* are well-discussed topics in the project management literature (see, for example (Ramasesh & Browning 2014) for the discussion about unknowns), and NDPs could benefit from the knowledge developed in the construction industry in order to understand how to better address them. For NDPs, this limited knowledge of the NDP site condition is caused by several factors, including the long time needed for construction and operations, and the poor knowledge and information management during both construction and operations (also sometimes caused by the transition from analogic to digital documents).

Hence, on the top of additional characterization (discussed for example by (Cross et al. 2012)), also best practices in knowledge and information management should be kept in high considerations not only during the NDP progress, but also during the construction and operations of the nuclear facilities (LeClaire & LeMire 2012).

Secondly, the need for clarity regarding the waste routes and about the availability of storage and disposal facilities have also been highlighted by several interviewees. Valencia (2012) discusses the topic of radioactive waste management for decommissioning projects. However, the findings derived from the interviewee's comment suggest that a need of integration between decommissioning *projects* and radioactive waste management *operations* is still needed. This is particularly true when a change in regulation occurs, for example triggering the re-classification of LLW into ILW (as one interviewee highlighted), or when changes in legislation result in landfill disposal being "*increasingly unavailable for some types of waste and more expensive for the wastes which are still accepted*" (Downey & Timmons, 2005, p.2), which therefore require new waste routes, and additional costs.

The abovementioned characteristics have been sparsely mentioned while describing NDPs (see for example (Laraia 2012b)), but the fact that they affect the time and cost performance of NDPs was not explicitly underlined.

Similar is the case of other NDP characteristics, including the need for clear end-state and scope definition. For NDPs, the clarity of the site end-state is a stimulating topics as, unlike for the planning and construction of new infrastructure, not only is the initial stage hard to describe, but also its end state is sometimes hard to define and its limited clarity affects the NDP performance (as it is hard to know how to achieve an aim, without having clarity regarding that). In other words, for decommissioning, not only "how to complete of an NDP" but also "what is the actual end-state" of an NDP, and even "what is ultimately the value of decommissioning" is complex to define. One interviewee particularly stressed this point, also explaining the importance of flexibility in decommissioning: *"You cannot define from the beginning the end of the [decommissioning] project! You have to be very flexible for the decommissioning project and you have to change sometimes totally the approach of your project"*.

Also concerning the definition of "value" in decommissioning, this could be particularly hard to define as at the end of a decommissioning project there is no new infrastructure to showcase, but rather a bare site. In the literature, the value of a project is often broadly defined as benefits versus costs. Conversely, for NDPs, the value of completing the NDP derives from the fact that a nuclear facility cannot just be abandoned and needs to be decommissioned, primarily due to safety[4] and security[5] reasons. In addition, ethics play a key role in decommissioning, as the future generations should not have to pay the costs of what past generations left (Taebi et al. 2012). Therefore, the management of NDPs taking into account the ultimate value delivered by an NDP, is worth particular attention and further investigation.

NDP characteristics mentioned only one interview

Moreover, some of the NDP characteristics that emerged from this research, have been mentioned during only one interview. However, they have significant relevance.

This is for example, the case of "incentives". In the construction industry, the principles of incentive contracting have been discussed, and the need to allocate risks and align incentive arrangements with the needs of both client and contractors have been explored (see for instance (Bower et al. 2002)). Financial incentives are not the only researched ones: Rose & Manley (2011), for example, discuss the effectiveness of both financial incentives compared to

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[4] The achievement of proper operating conditions, prevention of accidents or mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation hazards (IAEA, 2006b, p.102).

[5] The prevention and detection of and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material, other radioactive substances or their associated facilities (IAEA, 2006b, p.102).

initiatives to enhance relationships. Also on the topic of incentives, the experience of Rocky Flats NDP, is exemplary. Rocky Flats was a military nuclear weapons facility that produced plutonium and enriched uranium from 1953, and stopped operations in 1989. It was owned by the US Department of Energy (DOE), was managed by a series of weapons contractors, and during its decommissioning, its waste was shipped to other states in the US (DOE 2013; Cameron & Lavine 2006). 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 decommission it. Its decommissioning was however completed safely by a joint venture in less than 10 years and $3.5 billion. To promote the decommissioning of Rocky Flats, a target-schedule contract with very high incentive for early completion was signed, and one of its particularities surrounded the incentives agreements. Indeed, in order to avoid both that the employees prolonged their employment or that they quit earlier than expected (i.e. when their skills were still needed), the incentives for completion against target were high, but not all the bonuses were paid immediately (Cameron & Lavine 2006; Whinch 2010). These incentive agreements were one of drivers for the success of Rocky Flats decommissioning.

Similar is the case of the interviewee's comment referring to the need to design the nuclear facility with decommissioning in mind, which was also mentioned by only one interviewee as affecting the NDP performance. However, the need to "design for decommissioning", or as Dinner (2012) emphasises, design *and operate* to facilitate decommissioning, is an important finding not only for NDPs but mostly for nuclear new build.

Lastly, it has to be kept in mind that, in this study, interviewees were selected among senior NDP practitioners with managerial experience. This might have limited the (personal) considerations on the role played by project managers and the importance of his/her leadership style, a well-known topic. Turner & Müller (2007, p.49), for example, focusing on the project manager and his/her leadership style, affirm: *"Surprisingly, the literature on project success* *factors does not typically mention the project manager and his or her leadership style or competence as a success factor on projects. This is in direct contrast to the general management literature, which views effective leadership as a critical success factor in the management of organizations, and has shown that an appropriate leadership style can lead to better performance".* Concerning leadership, Turner & Müller (2005) also review the history of leadership and highlight several models of leadership and leadership styles that have been emphasized by the literature. Since then, the topic of leadership in projects has flourished, there being (Sankaran 2018; Yu et al. 2018) two recent publications on the topic. The brief reflection on leadership is thought-provoking, also taking, in consideration (once again) the experience of decommissioning Rocky Flats (DOE 2013), and its comparison with Sellafield NDP, presented elsewhere (Invernizzi et al. 2017a). In Rocky Flats NDP, at least three different leadership roles supported the transformational change that was necessary for the completion of the decommissioning activities, i.e. the idea champion, the sponsor and the orchestrator (Cameron & Lavine 2006, p.85), and played a pivotal role in the successful completion of the NDP. However, none of the interviewees involved in this study highlighted the need for inspirational leadership as relevant for the decommissioning project performance.

6 Limitations and Future Research

This research introduces several topics that should be investigated in depth and presents some limitations that should be addressed in future research.

The first limitation consists of the selection of the unit of analysis, i.e. commercial European NDPs, and future analysis on non-European NDPs is strongly envisaged to investigate whether the same or other NDP characteristics affect the NDP performance. Moreover, even if NDPs are extremely relevant decommissioning projects, other decommissioning projects exist and will grow in number in the near future (such as oil & gas, dams, and chemical plants decommissioning projects). Therefore, academic research should explore other types of infrastructure, eventually also comparing the findings with the ones from researching NDPs.

Additionally, interviewees were selected among senior NDP practitioners with managerial experience. However, this might have limited the (personal) considerations about the role played by project managers as well as his/her leadership. Hence, future research on the topic of leadership in the realm of NDPs is envisaged.

Moreover, future research could also investigate each single NDP characteristic that emerged from this research in detail more detail.

Lastly, their interconnectedness and their causal chain should be also investigated further, e.g. using soft system methodology (Checkland 2000)) or cognitive mapping techniques (Edkins et al. 2007), for example following (Lahdenperä 2012; Thunberg & Fredriksson 2018) for what concerns planning, contractual agreements and the availability of a reliable supply chain. In addition, with a growing number of decommissioning projects being completed, future studies should also consider the application of quantitative analysis (such as statistical tests and machine learning), as well as bridging quantitative and qualitative analysis (e.g. through qualitative comparative analysis (Schneider & Wagemann 2012)).

7 Conclusions

Historically, project management has mostly focused on the planning, design and construction of infrastructure. Conversely, even though decommissioning is a new, emerging, global techno-socio-economic challenge that is rapidly growing, decommissioning projects have been remarkably overlooked. Decommissioning projects are long, complex and expensive and there is limited understanding of what affect their cost and time performance. Hence, there is a need to investigate these projects, and promote the sharing of lessons learned.

Focusing on nuclear decommissioning, this paper aims to collect and analyse the NDP characteristics that affect the NDP cost and time performance, according to senior practitioners involved in European NDPs. More specifically, this paper addressed the following research questions:

- Which NDP characteristics affect the difference between time and cost estimates of NDPs and the NDPs' actual time and costs?

From the research, it emerges the importance of good knowledge of the site conditions, clarity in the waste routes and about the storage and/or disposal of the waste generated, and good relationship with the regulatory authorities, early planning and stable funding.

Lastly, this paper highlights the need to promote the sharing of transferrable learnings, not only among NDPs, but also, among decommissioning projects of other industrial sectors, such as Oil & Gas, certainly accounting for the difference between nuclear and other decommissioning projects, which will also need to be discussed in depth.

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Disclosure statements

The authors declare that there is no conflict of interest.

Appendix

United Kingdom	2006 discounted nuclear provisions [£million] (NDA 2006)	2011/2012 discounted nuclear liabilities [£million] (NDA 2012)	2015 discounted nuclear provisions [£million] (NDA 2016)	2016/17 discounted decommissioning & clean-up costs (NDA 2017)
Berkeley	360	659	589	1,658
Bradwell	506	506	210	1,736
Chapelcross	527	749	664	2,852
Dounreay	2,091	1,904	2,394	2,697
Dungeness A	504	647	525	2,035
Harwell and Winfrith	1,103	1,122	1,174	855
Hinkley Point A	543	699	651	2,102
Hunterston A	482	667	600	2,044
Oldbury	444	1,008	873	2,072
Sizewell A	354	778	709	1,982
Trawsfynydd	413	611	288	1,859
Wylfa	442	1,045	728	2,550
Spain				
Vandellos - 1	Decommissioning Projects (to reach C&M) completed with 4% cost overruns (IAEA 2011)			
Jose Cabrera	Progress of the Decommissioning: on time and within the budget (IAEA 2016a) while using (ENRESA 2016) cost overruns result >10% but < than 25%.			
France	2001 estimate [€million 2001] (CdC 2012)	2008 estimate [€million 2008] (CdC 2012)	2012 estimate [€million 2013] (CdC 2014)	
Chinon A	694,7	810,0	930,3	
St. Laurent	822,1	803,0	997,6	
Bugey – 1	348,4	412,0	585,9	
Brennilis	254,0	373,0	458,6	
Chooz A	245,1	220,0	344,4	
Super-Phoenix (Creys-Malville)	941,6	943,0	1311,5	
Germany	Greifswald Decommissioning [€million] (EWN 2011)(Wuppertal Institute 2007a)		Rückbau-Monitoring 2015 [€million] (Wealer et al. 2015)	
Greifswald	3,200		4,000	
Bulgaria, Lithuania and Slovakia	Estimate 2010 [€million] (European Court of Auditors 2016; 2011)	Estimate 2011 [€million] (European Court of Auditors 2016; 2011)	Estimate 2015 [€million] (European Court of Auditors 2016)	
Kozloduy 1-4 (Bulgaria)	1,118	1,243	1,107	
Ignalina (Lithuania)	2,019	2,930	3,376	
Bohunice 1-2 (Slovakia)	950	1,146	1,239	
Italy	Estimates “till deactivation” [€million]		Estimate at completion [€million]	
Enrico Fermi - Trino	291 (SOGIN 2003)		234 (iBasilicata 2012)	
Caorso	568 (SOGIN 2003)		240 (ANSA 2013)	
Latina	615 (SOGIN 2003)		704 (LatinaNotizie 2012)	
Garigliano	311 (SOGIN 2003)		360 (LatinaNotizie 2012)	

Table 1. NDPs in the UK, Spain, France, Germany, Bulgaria, Lithuania, Slovakia and Italy, adapted from (Invernizzi et al. 2019a).

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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 Greifswald 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

Table 2
Input costs data in UK, Spain, France, Germany, Bulgaria, Lithuania, Slovakia, and Italy.

United Kingdom	UK NDPs	2006 discounted nuclear provisions [£million] (NDA, 2006)	2016 discounted nuclear provisions [£million] (NDA, 2016)	2016/17 decommissioning & clean-up costs from the discounted lifetime plan (NDA, 2017a)	Is this NDP included in the statistical analysis?
	Berkeley	360	589	1658	Yes
	Bradwell	506	210	1736	Yes
	Chapelcross	527	664	2852	Yes
	Dounreay	2091	2394	2697	Yes
	Dungeness A	504	525	2035	Yes
	Harwell and Winfrith	1103	1174	855	Yes
	Hinkley Point A	543	651	2102	Yes
	Hunterston A	482	600	2044	Yes
	Oldbury	444	873	2072	Yes
	Sellafield	17,831	53,200	119,930	No
	Sizewell A	354	709	1982	Yes
	Trawsfynydd	413	288	1859	Yes
	Wylfa	442	728	2550	Yes
Spain	Vandellós-1	Decommissioning Projects (to reach C&M) completed with 4% cost overruns (IAEA, 2011)			Yes
	Jose Cabrera	Progress of the Decommissioning: on time and within the budget (IAEA, 2016), while using (ENRESA, 2016) cost overruns result > 10% but < than 25%.			Yes
France	French NDPs	2001 estimate [€; million 2001] (CdC, 2012)	2008 estimate [€; million 2008] (CdC, 2012)	2012 estimate [€; million 2013] (CdC, 2014)	–
	Chinon A	694,7	810,0	930,3	Yes
	St. Laurent	822,1	803,0	997,6	Yes
	Bugey - 1	348,4	412,0	585,9	Yes
	Brennilis	254,0	373,0	458,6	Yes
	Chooz A	245,1	220,0	344,4	Yes
	Super-Phoenix (Creys-Malville)	941,6	943,0	1311,5	Yes
Germany	German NDP	Greifswald Decommissioning [€million] (EWN, 2011) (Wuppertal Institute, 2007)		Rückbau-Monitoring 2015 [€million] (Wealer et al., 2015)	–
	Greifswald (Germany)	3200		4000	Yes
Bulgaria, Lithuania, Slovakia	Bulgarian, Lithuanian, Slovakian NDPs	Estimate 2010 [€million] (European Court of Auditors, 2011, 2016)	Estimate 2011 [€million] (European Court of Auditors, 2011, 2016)	Estimate 2015 [€million] (European Court of Auditors, 2016)	–
	Kozloduy 1–4 (Bulgaria)	1118	1243	1107	Yes
	Ignalina (Lithuania)	2019	2930	3376	Yes
	Bohunice 1–2 (Slovakia)	950	1146	1239	Yes
Italy	Italian NDPs	Estimates "till deactivation" [€million]		Estimate at completion [€million]	–
	Enrico Fermi - Trino	291 (SOGIN, 2003)		234 (iBasilicata, 2012)	No
	Caorso	568 (SOGIN, 2003)		240 (ANSA, 2013)	No
	Latina	615 (SOGIN, 2003)		704 (LatinaNotizie, 2012)	No
	Garigliano	311 (SOGIN, 2003)		360 (LatinaNotizie, 2012)	No

publications listed above and preliminary scoping interviews was prepared. The questionnaire contained one open question (i.e.: "*in your opinion, which NDP characteristics mostly impact on the NDP performance, in terms of cost and time?")* and 29 closed questions. The complete list of NDP characteristics collected both through secondary and primary data are presented in the appendix in Table 4, Table 5 and Table 6, while Table 3 in section 3 summarizes the results.

Table 4, Table 5 and Table 6 respectively list the country-specific, site-specific and management-related NDP characteristics that have been highlighted by the respondent either in the first (and only) open question of the questionnaire (data collection – A), and that have been discussed during the interviews, as included in the closed questions of the questionnaire (data collection – B).

Interviewees were chosen primarily according to their experience of at least one of the NDPs of Table 2, and at least one person with experience of one of the NDPs was interviewed. In total, 35 semi-structured interviews with NDP experts were performed. The interviewees covered the following countries: UK, France, Italy, Spain, Germany, Lithuania, Bulgaria, Slovakia, Sweden, Finland, Switzerland and the Netherlands. More than 80% of the interviewees had more than 10 years' experience in the nuclear decommissioning industry. The collection of primary data was fundamental to make explicit the recent, "tacit knowledge" gained on-field by practitioners.

The list of NDP characteristics was used to describe NDPs systematically. To do this, the NDP characteristics were operationalized into binary, categorical variables. So, for example, for the NDP characteristic "There is an ILW storage available on site", the binary answer Yes/No was used to differentiate NDPs that have a ILW storage available on site, from the ones that did not. Similarly, the NDP performance were operationalized into binary, categorical variables, as explained in section 2.2. First of all, however, the statistical tests suitable to investigate small sample sizes and categorical variables need to be selected. This is described in section 2.1.2.

2.1.2. Selection of statistical tests suitable for small sample size

The selection of statistical tests that are suitable to be implemented on small sample sizes, which is the case of NDPs, is fundamental. The Fisher's exact test is appropriate to test the association between variables in the context of nuclear decommissioning (Invernizzi et al., 2017a).

The Fisher's exact test uses binary categorical data in the form of contingency tables as input, i.e. tables showing the distribution of one variable in the rows and the other in the columns, as illustrated by a generic contingency table in Table 1. The table reports the number of cases belonging to each of the four cells. The Fisher's exact test is then able to identify whether a single NDP characteristic (i.e. an "independent variable") presents an association (or not) with the NDP performance (i.e. the "dependent variable"), which in this paper consists of (the loosely termed) "NDP cost overruns".

The Fisher's exact test is suitable to be applied to the context of

Table 3
P-values of the Fisher's exact test and the Barnard's test lower than 10%.

NDPs characteristics that show an association with the NDP performance		p-values lower than 10% with Fisher's Exact Test				p-values lower than 10% with Barnard's Test			
		No Cost Overruns	Cost Overruns Within 10%	Cost Overruns Within 25%	Cost Overruns Within 50%	No Cost Overruns	Cost Overruns Within 10%	Cost Overruns Within 25%	Cost Overruns Within 50%
Country-Specific NDP characteristics	The NDP is in the UK	4.47%	4.89%			2.68%	2.47%		
	The NDP is in France						6.87%		
	The country scores a corruption perception index > 80	8.36%				4.95%	5.50%		
	The legal timeframe for review of decommissioning plans is less 2 years	5.23%	8.20%			2.71%	4.14%		
	There is a complex and multi-layered governance	4.81%	8.36%			2.68%	4.28%		
	There is a separate external funding		5.95%			8.02%	3.56%		
	There is a regulated and separate internal fund of the NPP operator, with some protection against insolvency of the operator						6.87%		
	The government funds the whole NDP	8.36%				4.95%	5.50%		
Site-Specific NDP characteristics	The facility started construction before 1960	1.27%	0.61%			0.54%	0.21%		
	Stable funding is guaranteed until the end of the NDP					8.9%			
	The NDP consists of a group of facilities (i.e. more than one reactor on site has to be decommissioned)	3.72%				2.67%	6.87%		
	The facility has a net capacity higher than 200 MW but lower than 600 MW		4.96%				2.46%		
	The facility has a net capacity higher than 1000 MW		6.73%			8.0%	2.86%		
	There is a 'buffer zone' available on site								7.56%
	There is a ILW repository available in the country	4.81%	8.36%			2.68%	3.56%		
	There is a ILW storage available in the country and on site	7.13%			8.27%	3.88%	9.79%		8.44%
	There is a HLW storage available on country and on site							6.33%	

NDPs since (Leach, 1979; Freeman and Campbell, 2007):

- It investigates the association between variables in the presence of a small data sets (< 30 cases), which is the case of NDPs;
- It uses categorical binary data in the form of a contingency table, which is a way to be more objective in the operationalization of independent variables;
- It is a non-parametrical statistical significance test, i.e. it does not require assumptions about distributions (in particular, no normality is assumed);
- It is an exact test, i.e. the probability of an association existing between the variables can be calculated exactly.

Moreover, Kroonenberg & Verbeek (2017) recently quoted the specific recommendation for 2 × 2 tables by (Cochran, 1952, p.334) and (Cochran, 1954, p.420), explaining: "*Use Fisher's exact test (i) if the total N of the table < 20, (ii) if 20 < N < 40 and the smallest expectation is less than 5"*. Additionally, McDonald (2014, p.77) stated that the "*Fisher's exact test is more accurate than the chi-square test or G–test of independence when the expected numbers are small. I recommend you use Fisher's exact test when the total sample size is less than 1000*". In 1995, Martin (1995) already pointed out how the Fisher's exact test is simple to compute, available in almost all statistical packages, and it is valid from the unconditional point of view (Martin, 1995, p.590). These are some of the main reasons why the Fisher's exact test has been traditionally used to test the relationship between two variables when dealing with small sample sizes.

Nonetheless, the Fisher's exact test has also been often criticized for being too conservative (Routledge, 1992; Hasselblad and Lokhnygina, 2007; Lydersen et al., 2009), and other tests have been suggested by the literature to overcome this drawback. Hasselblad and Lokhnygina (2007) compare five tests for 2 × 2 tables in clinical trials, among which are the Fisher's exact test and the Barnard's Test. These two tests are both suitable for small sample sizes, and their difference lays on the fact that the Fisher's exact test is a conditional test, while Barnard's test is an unconditional test.

Conditional tests assume that the marginal of the rows and columns (i.e. the row and columns totals) are fixed (or "conditioned"), while in unconditional experiments, none of the row or column totals are prespecified by the experimenter (Ruxton and Neuhäuser, 2010, p.1508). For example, if the researcher decides to explore the potential association between sex of some birds and their willingness to try a novel food type, and he/she selects ten female birds and ten male birds, and introduces them into an experimental arena in which there is a novel food type, and the experiment is stopped after ten birds have consumed the food, both the total numbers of male and females and the total numbers of feeders and non-feeders have been fixed beforehand. So this is a (doubly) conditioned experiment (Ruxton and Neuhäuser, 2010, p.1508). Interestingly, a major part of the discussion about 2 × 2 tables is concerned with which approach, i.e. the conditional or the unconditional one, is the most suitable one (Andres, 2006) and there is still great controversy as to whether Fisher's exact test is effective when applied to non-conditional situations (Ruxton and Neuhäuser, 2010).

Martín Andrés et al. (2015) explain that conditional exact tests are well known to be more conservative and less powerful than unconditional ones "*because the loss of information as a result of conditioning may be as high as 26% (*Zhu and Reid 1994*)"* (Martín Andrés et al., 2015, p.1). Andres advocates the Barnard's test as the principal alternative for the Fisher's exact test (Andres, 2006, p.4) as well. However, this author also underlines that *"the differences between the two methodologies are greatly diminished for sizes above 50, and even more so in contingency tables of order higher than 2 x 2"* (Andres, 2006, p.1, p.1). Mehta and Senchaudhuri (2003) compare Fisher and Barnard, explaining more in detail the difference between the two tests.

Traditionally, the Fisher's exact test has been used more often than the Barnard's Test, the latter one being only recently employed in the area of medical research: for example, Shan et al. (2013) and Behrends et al. (2012) presented the results from the implementation of the Barnard's test in the medical field, while Proschan et al. (2016) applied both statistical tests on a research on the Ebola virus.

The recent interest in the Barnard's test is probably due to the fact that, in its earlier development, the Barnard's test was computationally too heavy. Indeed, in 2009, Lydersen et al. (2009, p.1159) explained how "*unconditional tests preserve the significance level and generally are more powerful than Fisher's exact test for moderate to small samples, but previously were disadvantaged by being computationally demanding. This disadvantage is now moot, as software to facilitate unconditional tests has been available for years* […]". These authors also stated that, at the time of writing (i.e. 2008–2009), they were not aware of the Barnard's test being included in any available software (Lydersen et al., 2009, p.1166). Conversely, nowadays Barnard's test can be performed both with R (Tal, 2010) and Matlab (Cardillo, 2010). For these reasons, the Barnard's test is also deemed to be suitable to be applied in the context of NDPs.

In summary, drawing from previous research and the considerations mentioned above, as well as aiming to provide the reader with the most complete and transparent results, while still being aware of the limitations of the sample size of 24 NDPs and the quality of the input data, results of both the implementation of the Fisher's exact test and the Barnard's test are presented. This choice also derives from:

- the understanding and agreement with McDonald's concerns (2014), who writes "*If your data weren't significant with Fisher's but were significant with your fancy alternative test, they would suspect that you fished around until you found a test that gave you the result you wanted, which would be highly evil. Even though you may have really decided on the obscure test ahead of time, you don't want cynical people to think you're evil, so stick with Fisher's exact test*" (McDonald, 2014, p.80);
- having read the work by Camilli (1990), who compares different tests for 2 × 2 contingency tables, showing that the Barnard's test is theoretically superior, but the Fisher's exact test is still advocated as "*the most rational choice"* and *"the most defensible statistical test available*" (Camilli, 1990, p.135); but also
- acknowledging the work of Martin et al. (2004), which concludes that the Fisher's exact test *"can be used as an approximation to Barnard's exact test for a table with 0 or 1 fixed marginals, when the sample size is ≥ 100 or when the smaller sample size is ≥ 80, respectively […]"* (Martin et al., 2004, p.745).

Therefore, the output of both the Fisher's exact test and the Barnard's test is a p-value, which represents how likely it is that the results detected by the implementation of this statistical analysis could have resulted from chance rather than due to an actual association between the variables in question.

In this respect, the smaller the p-value, the more significant are the results. Since this paper investigates the NDP cost performance, drawing from (Ruxton and Neuhäuser, 2010), the one-sided p-value is reported. Consistently with the literature, the results from the implementation of the Barnard's test show lower p-values than the ones from the implementation of the Fisher's exact test (see section 3). This is thought-provoking, and can trigger the discussion concerning what is the "right" threshold to define the significance of the result (a plea that has been often made, but only rarely heard). The significance threshold for p-values can vary. In this paper, consistently with (Brookes and Locatelli, 2015; Locatelli et al., 2017a; Locatelli et al., 2017b), and following the considerations of Camilli (1990), who envisages to report significance levels only, rather that the dichotomous decision of either "significant" or "non-significant, the authors present the results from the implementation of the Fisher's exact test and the Barnard's test with a p-value lower than 10%. This means that the results regarding the association of variables must be dealt in a circumspect fashion.

2.2. Data collection based on the NDP cost performance

As mentioned in section 1, the units of analysis are European NDPs, intended as site-level projects, i.e. "one nuclear site undergoing decommissioning" is referred to as "one NDP". In the effort of collecting information on the maximum number of European NDPs undergoing decommissioning, publications in English, French, German and Italian were reviewed. The NDPs initially selected after this review are reported in Table 2, which collects and lists the publicly available information on the development of the estimates at completion of NDP. All the cost data refer to estimates at completion (i.e. "*the expected total cost of completing all work expressed as the sum of the actual cost to date and the estimate to complete*", as defined by the Project Management Body of Knowledge (PMBOK, 2013, p. 539)), let alone the one referring to Vandellós-1 NDP (in Spain), whose "final cost of work" is reported by the (IAEA, 2011, p.55).

During the collection process, it emerged that:

- All the NDPs in Table 2 were nuclear facilities that produced electricity, let alone Harwell NDP, that was nevertheless included in the pool of selected NDPs because (i) of the availability of data and (ii) it is coupled with Winfrith NDPs (which also included one reactor producing electricity), as both Harwell and Winfrith were managed together by Research Site Restoration Ltd, and earlier estimates are provided in conjunction;
- In the UK, the Nuclear Decommissioning Authority yearly publishes the cost estimates of the UK nuclear legacy. As mentioned in section 1, Sellafield NDP stands out as a complete outlier, being Sellafield's decommissioning estimates more than 70% than the UK overall. Therefore, Sellafield is not considered in the current analysis (see the last column on the right of Table 2);
- Greifswald is the only German NDPs selected and listed in Table 2, as in Germany the utilities are the reactor owners and there is only scattered information publically available about the development of decommissioning cost estimates in time. Some updates from the German approach to decommissioning are available on the World Nuclear Association Website (WNA, 2018), but cost information are very limited.
- There is no recent public information on the estimate at completion of the Italian NDPs. The latest information regarding the estimate at completion of the four Italian cases come from local news, in the years 2012–2013. Therefore, because of the unreliability and date of reference of these data, it was deemed inappropriate to include the Italian NDPs in the statistical analysis.

The last column on the right of Table 2 highlights which are the NDPs that have been ultimately selected for the current analysis.

In summary, in the effort to generate evidence as well as to guarantee the maximum possible reliability of the results with the limited data and limited quality of the information available, 24 European NDPs have been selected through purposive sampling (Palinkas et al., 2015) for the implementation of the statistical analysis.

2.3. Operationalization of the NDP characteristics and the NDP performance

The NDP characteristics collected through the literature review and the semi-structured interviews, as well as the NDP performance in terms of "cost overruns", are categorical variables that need to be operationalized into binary constructs to allow the implementation of both the Fisher's exact test and the Barnard's test. The operationalization of these variables, that consists in coding real data (quantitative, qualitative, complex and uncertain) into "formalised constructs" (as defined by Lee and Lings (2008)) to describe NDPs through a list of binary categorical variable (i.e. both the NDP caracteristics and the NDP performance), is challenging. In fact, characteristics 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 explained by Rossiter (2002)), while other characteristics, such as "the stakeholders' engagement", consists of a mix of qualitative and quantitative information.

For example, in the attempt to operationalize the stakeholders' engagement, it will result extremely hard to answer the question: "*was the local community surrounding the NDP engaged early and timely*?" with either a "Yes" or a "No". In fact: what does "local community" exactly mean? What is the meaning of "engagement"? What does "early and timely" refer to? To what extent the response of the local community to this "engagement" was actually considered during the development of the NDPs? These are only some of the questions that arose when trying to investigate NDPs social aspects. This is to exemplify the reasons why some NDP characteristics cannot be operationalized. Social aspects, however, have been discussed at a "macro-level" in (Invernizzi et al., 2017b) and at a "micro-level" in (Invernizzi et al., 2018d).

Hence, not all the NDP characteristics that impact on the cost overruns either according to the literature or the interviewees (or both) have been operationalized in a binary way, and are therefore not tested through statistical analysis. The complete list of NDP characteristics that emerged from the literature and/or in the semi-structured interviews is discussed in (Invernizzi et al., 2018b) and presented in Table 4, Table 5 and Table 6, together with comments on their operationalization.

The NDP performance is assessed in terms of cost overruns, which should ideally be rigorously calculated as discussed and described by Invernizzi et al. (2018c). To calculate the cost overruns, drawing from Thompson (2009), the earlier ("initial") estimates are adjusted for the yearly inflation measured by the consumer price index (that can be found in the OECD official website (OECD, 2017)). The yearly inflation of Bulgaria comes from the World Bank official website (The World Bank, 2018) as it is not available in the OECD official website.

Costs are firstly expressed in costs in 2015 currency, i.e. they are actualized using Eq (1), where c_t is the time when the estimation are defined (see Table 2) and c_{t+1} is the costs actualized using the annual inflation i_{t+1}, iterated until all costs refer to 2015. Cost overruns are then calculated as in Eq (2), where C_{end} refers to the latest estimates and $C_{initial}$ refers to earlier estimates. Regarding the UK, data from 2006 to 2016 are the ones taken into account as respectively the "initial" NDP estimates at completion ($C_{initial}$) and the "latest" NDP estimate at completion (C_{end}). UK data from 2016/17 have not been used since the denomination of the costs presented in these reports changed from "nuclear provision" to "decommissioning and clean-up costs", which implies a possible change of scope in the decommissioning activities that would make the data not comparable.

$$\boldsymbol{C_{t+1}} = \boldsymbol{C_t} * (1 + \boldsymbol{i_{t+1}}) \tag{1}$$

$$\text{Cost Overruns [\%]} = \frac{\boldsymbol{C_{end}}[\boldsymbol{currency}] - \boldsymbol{C_{initial}}[\boldsymbol{currency}]}{\boldsymbol{C_{initial}}[\boldsymbol{currency}]} \tag{2}$$

Fig. 1 plots the NDP cost overruns against their latest estimates at completion, showing that there is no evident correlation between their estimates and their cost overruns. Cost overruns range from −67% to +60% and estimates range from the €94.6 million of Vandellós-1 (Spain) to the €4billion of Greifswald (Germany). As there is limited agreement on what is the threshold after which a project should be considered affected by cost overruns (e.g. does cost overruns occur when final costs are 2% higher than the initial estimates? Or 10% higher? Or 50% higher?), NDPs are grouped according to their cost overruns, following the literature. More specifically, NDPs are grouped using the following arbitrary threshold, i.e. if there is no cost overruns, if their cost overrun is within 10%, as in (Brookes and Locatelli, 2015), within 25%, as in (Merrow, 2011), and within 50%, because Fig. 1 shows a considerable gap between Bugey NDP, compared to Brennilis NDP and Iganlina NDP.

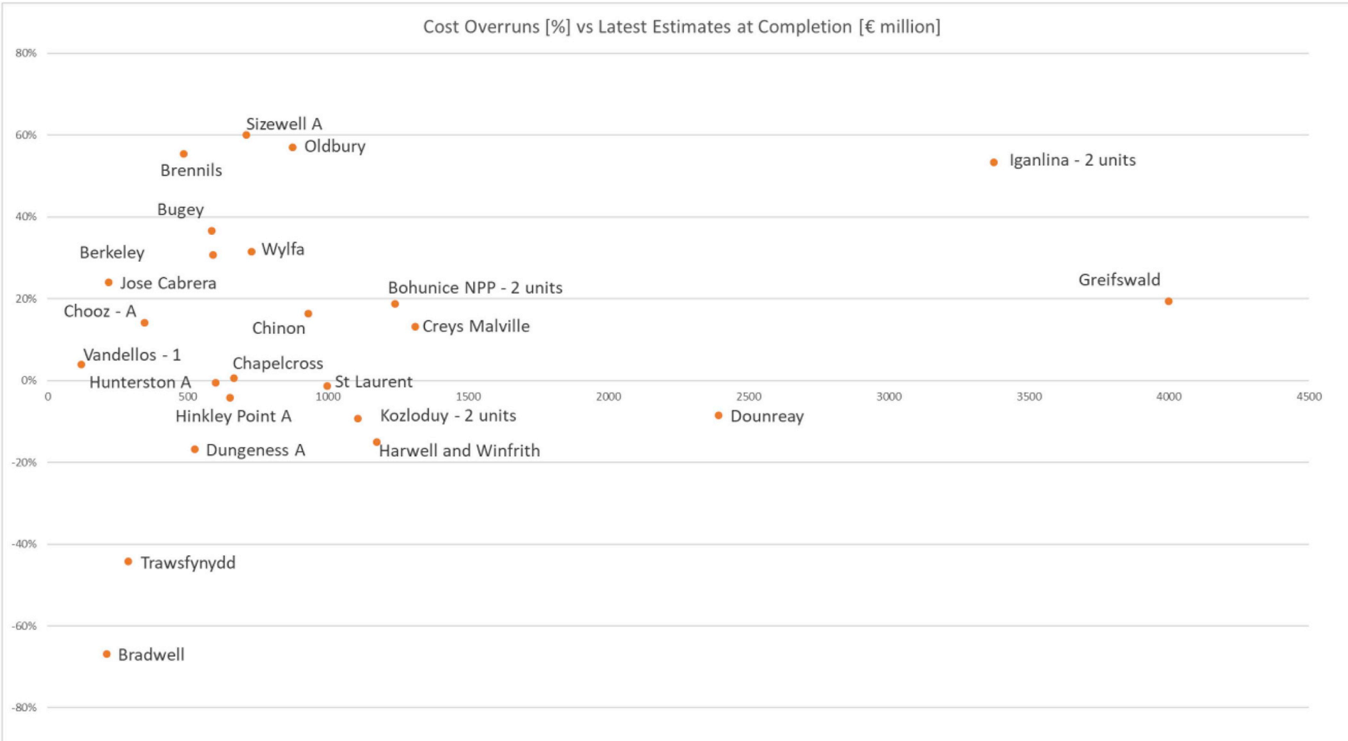

Fig. 1. NDPs Cost Overruns [%] vs NDPs Latest Estimates at Completion [€ million].

After both the NDP characteristics and the NDP performance are coded into binary variables, each NDP characteristic is tested against the NDP performance. For each NDP characteristic, a contingency table (like Table 1 in section 2.1) is built, and both the Fisher's exact test and the Barnard's test are applied. The results from this implementation are in section 3.

3. Results of the statistical analysis

Table 3 lists the p-values that result from the implementation of the Fisher's exact test and the Barnard's test, and that are lower than 10%. Several considerations can be drawn from these results.

The first consideration is that of the ~80 independent variables (i.e. the NDP characteristics) that have been collected, operationalized, clustered, summarised and tested against the dependent variable "NDP cost overruns" using four different thresholds, only 17 NDP characteristics show a p-value lower than 10% according either to the Fisher's exact test, the Barnard's test or both. This means that for each of these 17 NDP characteristics, it is not possible to hypothesise that there is no association between each single NDP characteristic and the NDP performance assessed in terms of cost overruns. In other terms, the implementation of these statistical tests provides means to highlight the NDP characteristics that present a possible association with the NDP performance.

The second consideration consists in the fact that, as expected and explained in section 2.1, the p-values from the Fisher's exact test are usually higher than the ones calculated using the Barnard's test. This is caused by the fact that Fisher's exact tests is generally more conservative. Therefore, it is possible to underline (once again) that the choice of the statistical tests to implement is fundamental, and has to be clearly and transparently presented. Indeed, as in the example of this paper, some NDP characteristics have a p-value lower than 10% only according to the Barnard's test and would not have emerged if only the Fisher's exact test was implemented. This is for example the case of the variable "stable funding is guaranteed until the end of the NDP" and "there is a 'buffer zone' available on site", which emerge from the Barnard's test. In this situation, probably even more than in others, it is necessary that the knowledge of the researchers comes into play to discuss more in-depth the meaning of the lower p-values, as well as the actual relevance of the operationalized NDP characteristics. Similarly, it is important to underline that the absence of an association does not mean that the corresponding NDP characteristic is not relevant, but simply that this association does not emerge from the implementation of the statistical tests on the specific sample of European NDPs that have been selected, and/or that the information available for the operationalization were not sufficient to highlight an association. In other terms, it is not possible to reach any conclusion on the NDP characteristics that do not have a p-value higher than 10%.

The third consideration derives from the need to stress the importance of the researcher's role in the techno-socio-economic explanation of the actual relevance of the NDP characteristics that emerge from the statistical analysis.

Some NDP characteristics that emerge from the application of the statistical tests, are particularly interesting food for thoughts. For example, the NDP characteristic "there is a complex and multi-layered governance" could trigger the thought that a complex governance system could support the management of complex projects, e.g. by supporting the NDP progress at different levels (e.g. long-term strategic level vs day-to-day operations) and from different perspectives (e.g. from the financial perspective, to the project-control perspective, etc.). Conversely, it could be conjectured that a complex governance is actually causing cost overruns due to the additional indirect costs. This dilemma can be solved only by going back each single NDPs, and deepening the investigation about governance in each one of them.

Other examples of NDP characteristics that emerged from this analysis and are worth further investigation are surely two site-specific NDP characteristics, i.e. the fact that "the NDP consists of a group of facilities" and that "there is a ILW storage available in the country and on site". Indeed, the first one can trigger the thought that if there is more than one reactor to decommission on site, lessons learned from the first one can be transferred to the second one, and the possibility to re-employ the same team can be a considerable advantage; the second one can suggest to check the interdependencies between waste management operations and decommissioning before undertaking (or progressing with) the NDP.

Similarly, the need to have sufficient space on site (a "buffer zone") for the decommissioning and waste management activities is envisaged to be further analysed, both in light of previous research (Invernizzi et al., 2017), and because it was particularly stressed during the interviews. One interviewee, for instance, explained: "*In Fountain-aux-Rose [NDP, in France], the site is so small! Inside the city! It is a huge struggle for them because they don't have enough room to make a new building, to make an interim storage for waste … so they have to create special access to remove directly waste, as soon as the waste is packed, they send it!*".

Another interviewee also provided an empirical example: "*In Jose Cabrera [NDP, in Spain], cooling towers went down … one each day! They had been built in the 90ies, they were not concrete-based and they have been dismantled one by one, one day after the other. The objective of their demolition was to create more space on site! Only a little amount of the material from the demolition has been re-used. And the scrap metal was sent to a melting facility.*"

This suggests the need to plan for decommissioning, even before the start of the construction of a nuclear facility.

4. Discussion

This paper investigates the association between project characteristics and project performance in the nuclear decommissioning industry through statistical analysis. The originality of this research lays on both the methodological approach developed to investigate NDPs (and described in this paper) and on its application on NDPs (which has an illustrative purpose).

In terms of methodological development, compared to previous research, this paper implements the Barnard's test alongside the Fisher's exact test to investigate the NDP characteristics that mostly impact on the NDP performance: as the Barnard's test is less conservative than the Fisher's exact test, the p-values derived with Barnard are lower than the ones derived from the implementation of Fisher. This was anticipated by McDonald's comment, who suggests to use the Fisher's exact test to avoid critics regarding the deliberate choice to use less conservative tests (McDonald, 2014). The Barnard's test is an unconditional test that is suitable to test the association of categorical variables as it is more powerful than other tests (Ruxton and Neuhäuser, 2010). Therefore, in order to provide the reader with the most complete and transparent set of results, p-values lower than 10% resulting from the implementation of both tests are presented.

Moreover, the NDP performance in terms of cost overruns has been operationalized following the literature using three different thresholds, i.e. 0%, 10%, 25% and 50% of cost overruns, because there is no "universal" agreement in the literature regarding which percentage of over budget can actually be considered a "cost overrun" (e.g. 10% according to (Brookes and Locatelli, 2015), 25% according to (Merrow, 2011), etc.). Also, different threshold-percentages were considered to suggest that larger thresholds should be used to capture the presence of greater uncertainties regarding the initial and final estimates at completion. Indeed, "*the determination of an accurate cost overrun can only be made by excluding cost increases during project elaboration. These are costs that occur between the initial budget established at definition phase and the final approved budget before work commences. Such costs should be regarded as part of the project initiation process prior to establishing final budget*" (Olaniran et al., 2016, p. 128).

Additionally, the NDP characteristics have been operationalized not only using secondary data, but also using primary data from semi-structured interviews, which can be used to update the information previously collected and to "make explicit" the tacit knowledge of experienced practitioners. Indeed, the information collected through the semi-structured interviews has been firstly analysed through qualitative content analysis (Hsieh and Shannon, 2005), used to complement the information from the literature, and then operationalized (when possible) into binary, categorical variables, so that the selected statistical tests can be applied.

Concerning the operationalization of the NDP characteristics, however, it is important to highlight that, even complementing the literature with information from semi-structured interviews, not all the NDP characteristics listed in Table 3 could be operationalized for all the 24 NDPs. More specifically:

- "The legal timeframe for review of decommissioning plans is less than 2 years" has been operationalized for 22 NDPs;
- "There is a ILW storage available in the country and on site" has been operationalized for 21 NDPs;
- "There is a HLW storage available on country and on site" has been operationalized for 17 NDPs.

This is due to either a lack of information in the references used to operationalized the NDP characteristics and/or is caused by the situation where, in the absence of recent and reliable, publically available documents, even the answer of the interviewee(s) was still too vague to guarantee a transparent operationalization of the NDP characteristic for the specific NDP under scrutiny. For example, the NDP characteristics "there is a ILW storage available in the country and on site" received firstly a positive answer that was disproved soon after, when the interviewee specified that the ILW storage was currently under construction, while in this investigation, the focus was put only on already operational facilities (as specified during the interviews).

The possibility to operationalize each NDP characteristics only for some of the 24 NDP obviously affected some NDP characteristics more than others, and further research could tackle this limitation by systematically collecting new, updated information that will be available in the future, as NDPs progress. However, even without having operationalized 24 NDPs, p-values lower than 10% for the abovementioned NDP characteristics were reached.

In terms of practical implication, this paper suggests a way to investigate the project characteristics that impact on the project performance in a systematic way. Therefore, the statistical tests presented in this paper could be re-applied to other contexts (e.g. Oil and Gas decommissioning) and provide new, fascinating insights.

Lastly, as often happens, collecting data through interviews provides a large amount of unexpected and relevant information, which were not possible to operationalize into binary variables. For instance, among others, two of the site-specific NDP characteristics raised the interested of the researchers as particularly stressed by some interviewees. These were: (i) the removal of a layer of contaminated concrete to dispose of the remaining concrete as conventional waste, and (ii) back-filling the voids created on site with non-contaminated material from the demolition were discussed. The activity of removing contaminated concrete to dispose of the remaining concrete as conventional waste received mixed answers, while back-filling was judged positively by most of the interviewees. Indeed, although the removal of a layer of concrete is envisaged as a way to reduce the waste volume and therefore ultimately reduce the costs of waste storage and disposal, it was judged by more than one interviewee not to be as efficient as expected. Back-filling, on the other hand, can both reduce the amount of material to be transported off-site and the amount of material that is needed on-site to fill the voids left after the removal of underground structures, and was therefore seen positively by the interviewees.

Removal of contaminated concrete and back-filling, however, are just two of the characteristics that were particularly stressed during the interviews. Therefore, a follow-up work consists in the systematic analysis of the qualitative information collected during the interviews.

5. Limitations and scope for future developments

Despite marking a major step towards the rigorous investigation of decommissioning projects, this paper has some limitations. The first one that affects this study is the quality of the cost data. Indeed, cost data have been collected from publicly available sources and often only a limited explanation regarding the assumptions underlying the calculation of these cost data is available: for example, the NDP estimates at completion refer to different stages of the NDP development (an information which is rarely specified in publically-available documents), and there is very limited knowledge about how cost escalation is taken into account and how contingencies have been calculated. Moreover, in this paper, for the calculation of the cost overruns, the consumer price index has been used to account for inflation, even if this index is a "particularly poor choice" (Hollmann, 2016, p.68), e.g. compared to other indices (such as the chemical engineering plant cost index (Hollmann, 2016, p.68–69)). Indeed, many indices exist (e.g. commodity indices, labour price and economic indices (Hollmann and Dysert, 2007, p.3)). However, due to the unavailability of decommissioning-related indices, the authors preferred to avoid to add further assumptions and complexity on poor-quality input data, and strongly suggest future research on this topic.

Indeed, the aim of this paper is to present an approach to test the association between the NDP characteristics and the NDP performance, and presents its implementation with the available data with a purely illustrative purpose.

Greater understanding of the specific assumptions underlying cost data could be a development of this research, including the specifications of the items that are included in the estimates, boundary conditions and limitations, decommissioning strategy description, end point state, changes in the regulations and technologies (Varley and Rush, 2011), through the description of how uncertainties in the cost estimating process are addressed (Torp and Klakegg, 2016), how currency (Love et al., 2005) and escalation are taken into account (acknowledging that it is not driven by practices used by companies or project managers (Hollmann and Dysert, 2007, p.2), and how uncertainties are tackled (IAEA/OCED-NEA, 2017).

The second limitation is that this analysis is bounded to European NDPs. This limitation stems from the choice of the authors to limit this research geographically, as both country-specific and site-specific physical characteristics are considerably different in non-European contexts. For example, the regulatory environment and the number of NPPs that have been built in the US are considerably different than the ones in Europe; moreover, the size of the licensed site and the free space available to progress with the decommissioning activities (generally bigger in the US than in Europe) are also dissimilar. Additionally, the US Nuclear Regulatory Commission (NRC) has specific requirements regarding the funding adequacy, i.e. every US NRC licensed NPP has to estimate decommissioning costs every other year and to submit the estimates to the US NRC to assure that adequate funding provisions are being made into approved decommissioning trust funds. Unregulated NPPs, however, are not required to submit cost estimates publicly (LaGuardia, 2016). These differences were also stressed during the interviews. For example, one interviewee from the UK compared the US regulations to the UK ones and emphasized: *"What was found to be hugely different, and the Americans were a bit shocked, was [that] our waste arrangement are entirely different here! We work at Best Practicable Means principle […]. An example of that would be: one of their waste strategies for major reprocessing facilities was that there was lots of concrete, [so] they would fill the hot cells up with concrete, slice them up in one thousand tons or two thousand tons pieces and just place them in the Low Level Waste repositories. And because they added so much concrete to it, everything was Low Level Waste. Now, that's unacceptable in this country! Unless it can be shown that it's Low Level Waste before you add concrete to it, you can't dispose of it that way!*". Future analysis could therefore also consider non-European NDPs and highlight new similarities, differences and potentially new lessons to be learned.

A third limitation of this research is that the results of the statistical tests only provide an "indication" of which NDP characteristics to scrutinize first. This means that no additional conclusion can be derived from the p-values, but conversely the low p-values only play the role of a "sieve" that provides an indication of the first NDP characteristics to look at (to begin with). Indeed, it is important to avoid to be affect by what has been called the "illusion of causality" by (Ahiaga-dagbui et al., 2015, p.866), as finding associations or correlations between factors does not necessarily mean that there is a relationship of causality between them.

The fourth limitation is the fact the statistical tests selected in this paper test the association of each single NDP characteristics against their performance in terms of cost overruns, without considering what a combination of two or more NDP characteristics could show. This latter point could be tackled through Qualitative Comparative Analysis (Schneider and Wagemann, 2012) in future research.

Lastly, corrections and/or controlling procedures such as false discovery rate or the family wise error rate could also be considered in further development of the statistics used in this paper. Meanwhile, each, single NDP characteristics that have been collected and listed in this paper can be scrutinized in-depth through single-case study or cross-case study. For example, in light of the results presented in Table 3, a cross-comparison of the different governance systems of the Bulgarian, Lithuanian and Slovakian NDPs (which are managed through the European Bank for Reconstruction and Development, but through different implementing bodies) is envisaged.

6. Conclusions

NDPs are a novel class of projects that has emerged in recent years, issuing new challenges to a number of different stakeholders, including policy-makers, project managers, employees on site, and the local community surrounding the NDP. Moreover, the NDP estimates at completion for many of these projects keep increasing, and there is a limited research embracing this area. Benchmarking is a way to tackle these challenges and understand which NDP characteristics mostly impact on the NDP performance, but it needs to be tailored to the case of NDPs. For this reason, a methodology based on benchmarking which includes cross-comparison and statistics has been developed specifically for NDP. This paper focuses on statistics and presents an approach to investigate the association between the NDP characteristics and the NDP performance, through the selection and application of two statistical tests.

The NDP characteristics that have been tested in the paper have been collected from the literature, complemented by empirical information from semi-structured interviews, analysed systematically and operationalized into binary variables (when possible). Then, the Fisher's exact test and the Barnard's test have been applied to test the association between NDP characteristics and NDP performance.

Results highlight 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). However, low p-values from statistical tests can only provide a first indication regarding which NDP characteristics to look at (to begin with), and it is the researcher that plays a pivotal role in discussing and further investigating the NDP characteristics that emerged from the application of statistics.

It is also necessary to iterate that the aim of this paper is neither to discuss the process of estimating costs, nor to propose a new model for costs estimation. This paper examines the relationship between the NDP characteristics and the NDP cost performance, applying two statistical tests suitable for small sample sizes on 24 NDPs with an illustrative purpose. However, the decommissioning industry is a growing industry, and more and more data and information on NDPs will be generated and collected in the very near future and could be fed into this approach, whose results could also ultimately inform project planners and cost estimators. Research on how to improve the NDPs performance has only recently started, and it will be a long journey, which needs to start with a first step. This research represents the first step towards a better selection, planning and delivery of NDPs.

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Appendix

Table 4
Country-Specific NDP characteristics

Country - Specific NDP Characteristics		Data Collection		Data Analysis	Comments
		A: Answer of the first, open question	B: Explicit question in the questionnaire	Operationalized for the statistical analysis	
Location and National Strategy	The NDP is in the UK, France, Spain, Germany, Bulgaria, Lithuania, or Slovakia	No	No	Yes	There is enough public information available for the operationalization for the statistical analysis
	The country scores a corruption index lower than 60 and/or lower than 80, as scrutinized by (Locatelli et al., 2017a)	No	No	Yes	
	The national strategy is "clearly defined" and/or did not change in the last 10 years	Yes	No	No	Even after the interviews, a univocal, unambiguous operationalization for the statistical analysis is extremely challenging
Regulatory Environm-ent	New "regulations or "changes" in the regulations occurred and affected the NDP (e.g. regulations become "more strict")	Yes	Yes	No	
	The legal timeframe for review of decommissioning plans is less 4 years and/or also less than 2 years (as in (OECD/NEA, 2010))	No	No	Yes	There is enough public information available for the operationalization for the statistical analysis
Ownership, Governan-ce & Funding	The Government or the operator has the ownership and responsibility to decommission	Yes	No	Yes	
	There is a complex and multi-layered governance	Yes	No	Yes	
	Funding is allocated yearly or until the end of the NDP	Yes	Yes	Yes	
	There is a separate external funding; there is a regulated and separate internal fund of the NPP operator, with some protection against insolvency of the operator; there are internal restricted funds by the NPP operator governed by the state; there are internal restricted funds by NPP operators (no regulation by the state) – operationalized as in (Irrek, 2016)	No	No	Yes	
Supply chain	There is an experienced and reliable supply chain	Yes	No	Yes	

Table 5
Site-Specific NDP characteristics

Site – Specific NDP Characteristics		Data Collection		Data Analysis	Comments
		A: Answer of the first, open question	B: Explicit question in the questionnaire	Operationalized for the statistical analysis	
Design & Construction	The design of the nuclear facility is a Pressurized Water Reactor (PWR), a Boiling Water Reactor (BWR), etc., with a capacity of less than 200 MW, less than 600 MW, etc.	No	No	Yes	There is enough public information available for the operationalization for the statistical analysis
	The construction of the nuclear facility started in the 60ies/70ies/80ies/etc.	No	No	Yes	
Site Operations & Waste Management	There are other facilities still operating on site while the NDP takes place	No	Yes	Yes	The interviews provided the information for the operationalization for the statistical analysis
	The NDP collects waste from other sites and/or other countries	No	Yes	Yes	
	Incidents/Accidents occurred during operations or decommissioning in the International Nuclear and Radiological Event Scale (INES)	No	Yes	No	This characteristic emerged from the interviews. However a univocal, unambiguous operationalization was extremely challenging
	(Unexpected) chemical and physical risks are present, e.g. asbestos, sodium, etc.	Yes	No	No	
	There is a "buffer zone" on site, i.e. there is enough space available for the decommissioning activities	No	Yes	Yes	The interviews provided the information for the operationalization for the statistical analysis
	LLW, ILW, HLW storage facilities and/or repositories are available in the country and/or on site	Yes	Yes	Yes	
	Spent fuel is reprocessed in the country and/or on site	No	Yes	Yes	

Table 6
Management-Related NDP characteristics

Management-Related NDP Characteristics:	Data Collection		Data Analysis	Comments
	A:Answer of the first, open question	B:Explicit question in the questionnaire	Operationalized for the statistical analysis	
The scope of the NDP is "clearly defined"	Yes	Yes	No	Even after the interviews, a univocal, unambiguous operationalization is extremely challenging.
The scope includes buildings remaining and/or includes the reuse of buildings for nuclear and non-nuclear purposes	Yes	Yes	Yes	The interviews provided the information for the operationalization for the statistical analysis
Planning started before the shutdown of the facilities	Yes	Yes	Yes	
Management tools like the Earned Value Management (EVM) are used to measure and report performance	No	Yes	No	Even after the interviews, a univocal, unambiguous operationalization is extremely challenging.
The NDP benefits from a knowledge management system to exchange information on site/in the country/globally and/or international organizations are supporting the NDP with publications and/or consultations and/or financially	Yes	Yes	No	

(*continued on next page*)

Table 6 (*continued*)

Management-Related NDP Characteristics:	Data Collection		Data Analysis	Comments
	A:Answer of the first, open question	B:Explicit question in the questionnaire	Operationalized for the statistical analysis	
Incentives are allocated on key milestones, when the actual performance meet and/or exceed the expected performance and/or are allocated to single employees	Yes	Yes	No	Even after the interviews, a univocal, unambiguous operationalization is extremely challenging, and it was not possible to collect enough reliable information on SPE/SPVs
There is an Special Purpose Vehicle/Special Purpose Entity (SPV/SPE) involved in the contracting agreements	No	Yes	No	
Pilot projects and/or mock-ups are used on-site and/or off-site	Yes	Yes	No	Even after the interviews, a univocal, unambiguous operationalization is extremely challenging.
Technologies that are new on site/in the countries have been/are used	No	Yes	No	
Extensive characterization is planned and performed and/or resulted to be accurate	Yes	Yes	No	
Waste routes are "clearly defined" and the interface between the "decommissioning organization" and the "waste management organization" is "well-managed"	Yes	No	No	This characteristic emerged from the interviews. However, a univocal, unambiguous operationalization was extremely challenging.
Activities to reduce waste, such as stripping of concrete/back filling/segmentation in situ/ etc. are planned/performed	No	Yes	No	Even after the interviews, a univocal, unambiguous operationalization is extremely challenging.
The NDP social culture needs to change during the transition from operation to decommissioning, as decommissioning is considered to be never ending; External project managers/consultants are employed to foster the "change of culture"; Employees are retrained for subsequent relocation/ compensated, e.g. through a severance agreement; The local community is strongly dependent on the activities carried on; The local community has been/is engaged early and timely and no protest arose that caused delays; The authorities and the environmental agencies been engaged early and timely and no delays occurred; etc.	Yes	Yes	No	These characteristics have been discussed in (Invernizzi et al., 2017b)

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Publication V

“The need to improve communication about scope changes: frustration as an indicator of operational inefficiencies”

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The need to improve communication about scope changes: frustration as an indicator of operational inefficiencies

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ABSTRACT
Early and timely sharing of information can provide a sustainable competitive advantage. However, even if lean information management aims to improve this information flow, it has mainly been investigated in 'operations-based' companies. This paper fills this gap, drawing upon the experience of the authors working within a large project-based company engaged in the 'engineer and manufacture to order' of a complex piece of equipment costing millions of dollars, for its strategic long-term client, both working in the same industrial field, i.e. nuclear decommissioning. This research investigates the information flow regarding scope changes between the project-based company and the long-term client adapting and applying a five-step framework to highlight operational inefficiencies, reduce the corresponding transaction costs and increase the overall company's competitiveness. This is exemplified through a particular case, but can be applied to other project-based companies dealing with strategic clients involved in long-term relationships.

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Information management; interorganisational relationships; performance improvement; scope changes; nuclear decommissioning

1. Introduction

There are many different interpretation of knowledge management and the lack of a clear distinction between knowledge and information management has been recognised as a major issue within the literature (Alavi and Leidner 2001; Bouthillier and Shearer 2002; Shih et al. 2012). Knowledge management is defined by Kaivo-oja (2012, 207; quoting Giland 2004) as the '*deliberate design of processes, tools, structures, etc., meant to increase, renew, share, or improve the use of knowledge represented in any of the structural, human and social elements of intellectual capital*'. Information management does not refer only to the gathering of past knowledge and lessons learned to be applied to current practices, but mainly to managing the data that are created on a daily basis, how they are stored, retrieved & shared, both within the company and eventually with clients and suppliers. The early and timely sharing of information can provide sustainable competitive advantage, especially to companies involved in interorganisational relationships (Oliver 1990). Still, '*too much distribution of information can lead to information overload which could paralyze action*' (Bouthillier and Shearer 2002, 16). Indeed, efficient information management can provide steady advantage to generate financial and economic benefits, only if the information flow is accurate, updated and complete.

Lean information management refers to the application of lean thinking to information management, where information management involves '*adding value to information by virtue of how it is organised, visualised and represented*' (Hicks 2007, 233). Lean information management can improve organisation performances by reducing inefficiencies, streamlining the information flow and focusing on establishing roles, responsibilities and practices in order to increase the overall value of information and knowledge (Bevilacqua, Ciarapica, and Paciarotti 2015; Ibbitson and Smith 2011). Lean management has historically been investigated in the field of operations and within 'operations-based' industries (e.g. automotive Taylor and Taylor 2008; supply chain management Martínez-Jurado and Moyano-Fuentes 2014; and health care Toussaint and Berry 2013), and only limited research has explored this issue in project-based companies.

Project-based companies (also called 'project-based firms'; Kujala et al. 2010) are defined as '*organizational forms that involve the creation of temporary systems for the performance of projects*', which '*conduct the majority of their activities as projects and/or provide project over functional approaches*' (PMBOK 2013; 552). However, the 'engineer to order' industry still suffers from the lack of a specific production planning and control process (Adrodegari et al. 2015) and only limited research on lean information management has been undertaken within the 'engineer to order' industry.

This paper fills this gap, drawing upon the experience of the authors working within a large Project-Based Company (called PBC) engaged in the 'engineer and manufacture to order' of a complex machine costing millions of dollars for its Long-Term Client (called LTC). Both the PBC and LTC belong to the same complex and highly regulated field, nuclear decommissioning. This research analyses the information flow between PBC and

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Table 1. Waste in manufacturing and corresponding waste in information management, adapted from (Hicks 2007).

Waste in manufacturing systems	Corresponding waste in information management	Comments
Overproduction	Flow excess	Flow excess is defined as the resources and activities that are necessary to overcome a lack of information
Waiting	Flow demand	Flow demand concerns the time and resources spent trying to identify the information elements that need to flow
Extra processing	Failure demand	Failure demand relates to the time and resources that are necessary to overcome excessive information
Defects	Flawed flow	Flawed flow includes the resources and activities that are necessary to correct or verify information, including unnecessary or inappropriate activities that results from its use

LTC relating to scope changes and how the information flow both influences and is influenced by the changes. Scope changes are here understood as any change to the project scope that requires an adjustment to the project cost or schedule (PMBOK 2013, 562). This study considers scope changes that arise both from clients and contractors, who need to communicate to the other party their additional requests or the necessity to address previous omissions or errors. These can easily escalate in long and complex projects (where complexity is intended here both as technical and organisational; Locatelli, Mancini, and Romano 2014).

According to Stuart et al. (2002), there are different types of contribution to knowledge, i.e.: (i) discovery, description, understanding; (ii) mapping, relationship building; (iii) theory validation, extension, refinement. This research falls in the first group, as it *discovers* the presence of frustration caused by operational inefficiencies, it provides guidance on how to *describe* these inefficiencies through visual representation and increase the overall *understanding* of the company's current-state.

The ultimate aim of this research is to show the importance of monitoring and addressing 'weak signals' (e.g. frustration) to deliver better performance. To do this, this paper adapts and applies a five-step framework to highlight operational inefficiencies, reduce the corresponding transaction costs, and increase the overall company's competitiveness.

2. Theoretical background

2.1. Transaction cost and information management

A transaction takes place when a service is exchanged across distinct interfaces (Williamson 1981), and transaction costs are related to the organisation of economic activities of a company (such as searching and information costs, bargaining and decision costs, and policing and enforcement costs; Durugbo et al. 2014). Notably, (Clemons, Reddi, and Row 1993; Stratman 2008) argue that the major components of transaction costs are associated with the collection and integration of information into the decision process and the cost of the risk that the other party will fail to meet the contractual obligations due to opportunism. Durugbo et al. (2014, 628) also state that when aiming at delivery reliability, information flow plays a pivotal role, both externally and internally, and that '*the interplay of vertical integration, market relations and long term, voluntary relations […] is required to effectively manage delivery-related integrated information flow*'. This statement is particularly relevant for the current research, and is aligned with the standpoint of Zhao, Hui, and Jianron (2006), who argue that information integration is the foundation of the broader supply chain integration. In fact, optimised information flow can facilitate delivery, supporting both internal and external interactions. Hence, there is a need to investigate empirically the efficiency of the information flow, especially for project-based companies in industrial sectors that are dealing with increased pressure for enhancing projects delivery, such as nuclear decommissioning (Invernizzi, Locatelli, and Brookes 2017a, 2017b), or public infrastructure construction projects, where tax payers pay for the additional costs (Love et al. 2017).

2.2. Information management and lean information management

In its endeavour of streamlining and optimising the information flow, lean information management has recently raised the interest of both practitioners and academics (Bevilacqua, Ciarapica, and Paciarotti 2015; Hicks 2007; Jaaron and Backhouse 2011). However, limited research has analysed the potential of lean information management in project-based companies. Lean thinking has to be adopted as a holistic business strategy, rather than an activity isolated in operations to reach its full potential (Fullerton, Kennedy, and Widener 2014). However, because of the considerable increase in the information generated, recorded, stored, retrieved and shared, the focus of information management needs to be extended to project-based, 'engineer-and-manufacture-to-order' companies.

Hicks (2007, 324) discussed the application of lean thinking on information management, reporting that '*fundamental to the successful application of lean is the identification of value, understanding of flow and characterization of waste*'. Waste, however, is more visible within manufacturing, but less tangible in the context of information, where the culture of 'performance measurement' is less developed. Nonetheless, Hicks (2007) argues that an analogy can be drawn, and waste in information management (failure demand, flow demand, flow excess and flawed flow) and in manufacturing (over processing, waiting, overproduction and defects) can be matched, as shown by Table 1. These waste categories can also be used to cluster the waste categories in lean information management i.e.: waiting, conveyance, inventory, correction, defects, incompatibility, unnecessary transfer of information and inappropriate systems (Hölttä et al. 2010, 1460).

In the current research, the authors argue that one indicator of operational inefficiencies consists of the 'weak signals' (such as frustration – see section 2.3), shown by human resources during their everyday activities concerning the information flow regarding scope changes. In this case, the 'waste' mostly consists of the time and effort required to generate, acquire and identify the additional (missing) information, but also of the time and effort spent to determine whether the information received is relevant and urgent or not, and the eventual 'mistakes' in judging its importance and/or activities that result from its use. This is exacerbated by the fact that project-based organisations have to deal with a huge number of non-repetitive information, not always accurate enough, and that cannot be easily tracked and/or that is not able to flow (Bevilacqua, Ciarapica, and Paciarotti 2015).

2.3. Operational inefficiencies and stakeholders' frustration

The discussion about the role of 'weak signals' in the organisational and institutional systems and strategic decision-making has been prolific in recent years (Kaivo-oja 2012). Acknowledging the ambiguity of the term 'signal', Sidhom and Lambert (2011, 42) affirm that signals can be classified as 'weak' if they are fragmented, embedded in '*a mass of useless information*' and characterised by '*low palpability*'. Sidhom and Lambert (2011) report the definition of 'weak signals' by Ansoff (1985), who defines them as *'warning (internal or external) events and developments that are still too incomplete to allow for an accurate estimate of their impact and/or to determine a full adapted response'*.

Following this definition of 'weak signals', the authors focus on frustration, anger, helplessness, powerlessness as described by (Baker et al. 2010; Ceaparu et al. 2004; Gelbrich 2010). Frustration might occur at an interruption of the goal attainment process, where a barrier or conflict is put in the path of an individual (Ceaparu et al. 2004) or depends on blame attribution (Gelbrich 2010), which means that people hold uncontrollable circumstances responsible for an aversive event. Frustration can be described as a sense of dissatisfaction or annoyance, and can be associated with confusion and boredom (Baker et al. 2010), and described as a milder version of anger (Gelbrich 2010). Helplessness is an emotion that results from the prospective evaluation of future perceived irrevocability to control an adverse situation; powerlessness refers to the feeling of being controlled by others (Gelbrich 2010).

These 'weak signals' of stakeholders' discomfort are challenging to identify and assess, and have been often overlooked and only limitedly investigated (Hölttä et al. 2010), mostly in the field of human–computer interactions (Baker et al. 2010; Bessiere et al. 2003; Ceaparu et al. 2004; Jefferson 2006) and behavioural research (Harrington 2005). Harrington (2005), for example, developed a frustration discomfort scale made of 47 items on a 5-point-likert scale, to quantitatively investigate the correlation between the coping inventory item and the frustration discomfort scale itself. Conversely, in its dynamic analysis, Grundy (2000) symbolically displayed the curves representing the 'energy of the team' and 'frustration over time', showing that over time, the 'energy level' of the team decreases as the 'frustration' increases. In the field of health care, Cogin, Ng, and Lee (2016) adopt a qualitative research design to investigate job attitudes (such as low morale and frustration) and operational efficiency.

It might be difficult to quantitatively measure weak signals of frustration, but weak signals of stakeholders' discomfort should not be ignored. Weak signals could and should be used to highlight the underlying cause of these complaints. This idea is based on the assumption that the 'frustration points' can be caused by operational inefficiencies, and that stakeholders' complaints can be used as indicators of these inefficiencies. During the fieldwork, weak signals of frustration, anger, helplessness and powerlessness, have been systematically recorded by the authors, and being the frequency and the repetitiveness of these comments and complaints striking, the authors derived a methodical investigation, described in the framework presented in section 4. This five-step framework stems from the consideration that the relationship between operational inefficiencies and weak signals of stakeholders' deserves more attention both from academics and practitioners.

Figure 1 illustrates the focus of the current research through the big red arrow, i.e. relationship between operational inefficiencies that can be the cause of frustration and other 'weak signals' of negative emotions. Indeed, this relationship is remarkably under investigated, especially when compared with the one between operational inefficiencies and business delays and cost overruns (dotted arrows in the lower part of Figure 1), and the relationship between both retrospective and prospective emotions and both confrontational and support-seeking coping responses (thin green arrows in the upper part of Figure 1 analysed by Gelbrich 2010).

3. Derivation of the research questions

Project-based companies involved in long-term relationships with their client(s) can be related to the corporate-financial interlock described by Oliver (1990), characterised by (1) severe market and regulatory constraints, (2) symbiotic contributions by participants, (3) potential for high-quality advice, (4) high unpredictability in availability or acquisition of capital and (5) external pressure to demonstrate financial viability. In this context, where several change orders are placed by LTC to PBC over decades, transaction costs connected to the communication between the two parties have become substantive. Moreover, several people in both organisations are involved in this long-term relationship (e.g. the programme and project managers, engineers, manufacturing employees, etc.), so the efficiency of the information flow (i.e. benefit of generating and sharing information vs its cost) has become crucial. In this kind of relationship, the two key flows are the material (i.e. the product delivered) and information (Prajogo and Olhager 2012).

Drawing upon the theory and the experience of the authors working in PBC and stemming from the research background described in Section 2, the authors have made a systematic bibliographic analysis related to the current study. Table 2 shows the number of publications from 2000 to September 2017, embracing the topics of transaction cost, lean management, lean information management, information management, scope change[1]. Interestingly, Table 2 shows that there have been some attempts to consolidate the concepts of transaction costs AND information management (95 publications), but only very limited research has focused on information management AND scope changes[2] (only 3 publications). This suggests that the two concepts have not been frequently juxtaposed, and that there is a gap in knowledge about the efficiency of the information flow regarding scope changes and its role in business. Only recently, Beauregard (2015) focused on cost overruns in the aerospace industry, presenting a lean risk management approach to reduce surprise and scope changes, emphasising that non-recurring engineering

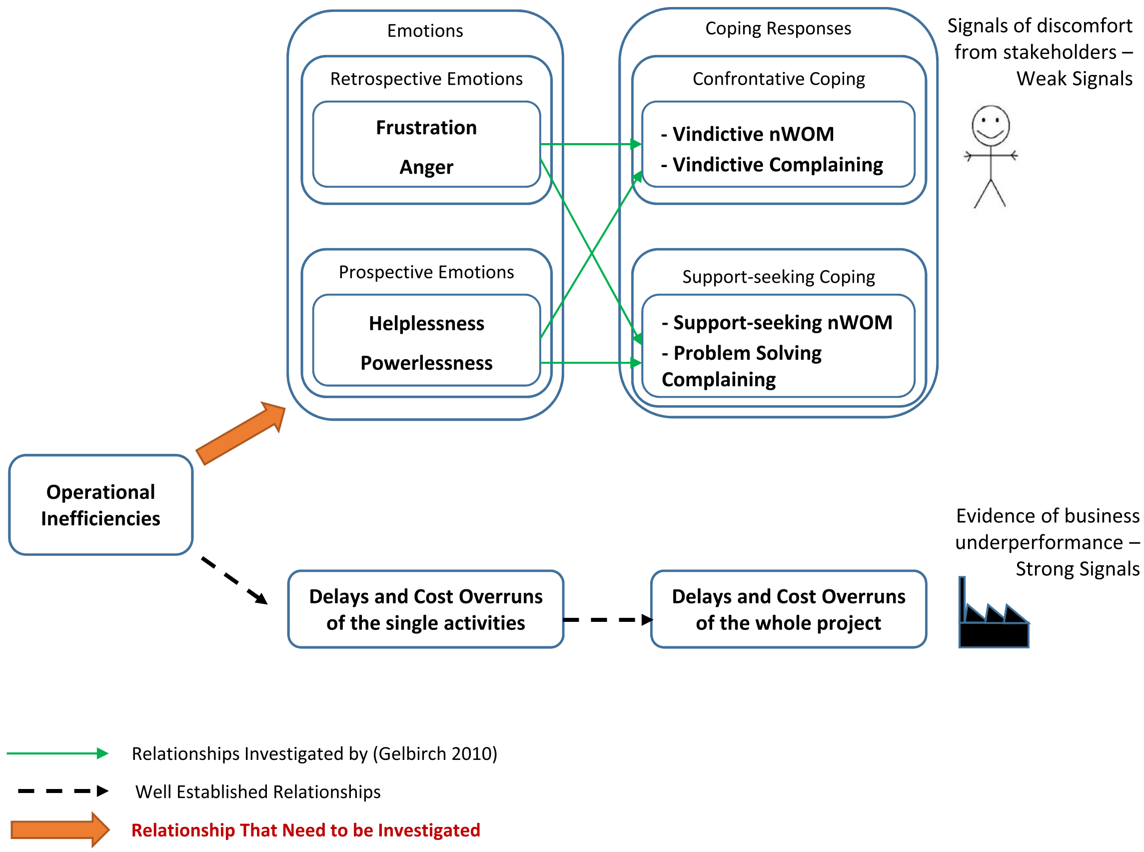

Figure 1. The direct consequences of operational inefficiencies.

Table 2. Focus of the literature review.

Number of results in Scopus from 2000 to September 2017	Transaction cost	Lean management	Lean information management	Information management	Scope change
Transaction cost	10,919	0	0	95	0
Lean management	–	801	0	35	0
Lean information management	–	–	12	12	0
Information management	–	–	–	93,713	3
Scope change	–	–	–	–	127

cost overruns negatively impact on the organisations' credibility as well as profitability. Cheng and Carrillo (2012) stressed the importance of extensive information sharing and constant communication to minimise changes during the product development. Interesting is also the study about information flow and changes by Childerhouse et al. (2006), who discusses the 'pains' experienced by automotive suppliers in achieving a change and the barriers to information flow, which the authors cluster into technological, cultural, financial and organisational. However, according to Love et al. (2010), unforeseen scope changes are one of the underlying condition for disputes for contractors, and the PMBOK emphasise the need of an integrated change control in the project communication management (PMBOK 2013, 304, 530–531). So, there is a need to address this topic.

Lean information management itself also remains remarkably under investigated (12 publications), but the year of publication highlight that there is a growing interest in the topic (the above-mentioned 12 research have all been published after 2007, and 7 of them have been published after 2013).

In order to fill the gap in knowledge on lean information management and impressed by the 'weak signals' of frustration showed by stakeholders in PBC and LTC regarding the information flow on scope changes already in the very early stage of the collaboration with PBC, the authors derived the following research questions:

RQ 1: To what extent should and could weak signals of stakeholders' discomfort be used to highlight operational inefficiencies on the information flow associated to high transaction costs?

RQ 2: How can communication and information management be improved to address the stakeholders' discomfort, optimise the information flow and ultimately increase the overall project performance?

Indeed, in the context of the current research, the concept of efficiency is worth unpacking, as interorganisational relationships address different objectives and are incentivised by different generalisable determinants, namely: (1) necessity, (2) asymmetry, (3) reciprocity, (4) efficiency, (5) stability and (6) legitimacy (Oliver 1990) and the movement from the market-mediated transactions to formal interorganisational arrangement might occur as an attempt to reduce transaction costs and increase the company's efficiency.

To answer to these research questions and tackle the challenges in communication, Section 4 develops and applies a systematic five-step framework, adapting business event analysis, event modelling and gap identification (Cadle, Paul, and Turner 2010). Section 5 provides a discussion of the results obtained from the application of the five-step framework on PBC and LTC. Section 6 summarises the conclusions and suggests the way forward to optimise the information flow process.

This research is empirically based and exemplified through the case of PBC and LTC, but the framework presented here can be applied on any project-based companies involved in long-term relationships with their strategic clients, such as the aerospace industry. The vast majority of the results will allow inferences to other industrial sectors as well, because challenges related to scope changes might affect all projects. Also, similarly to requirement management (Jallow et al. 2008), change management is an activity that needs to be performed throughout a project and not only during its early stage.

4. The five-step framework

The five-step framework developed by the authors is based on case research (Eisenhardt 1989; Stuart et al. 2002; Yin 2009; Zhang, Pawar, and Bhardwaj 2017) and implements lean information management following the approach proposed by (Bevilacqua, Ciarapica, and Paciarotti 2015) and (Wickramatillake et al. 2007). Similarly to (Ketokivi and Choi 2014), the authors use a case study because of its duality of being both situationally grounded and generalizable. However, lean information management has been remarkably under-investigated in project-based companies, so this paper presents the five-step framework developed and applied on the case of PBC and LTC to highlight inefficiencies and suggest improvement objectives.

The five steps are:

(1) Understanding of the context;
(2) Data collection and validation;
(3) Creation of the current-state;
(4) Analysis of the current-state (sometimes called 'as-is' analysis) and detection of inefficiencies;
(5) Development of improvement objectives through the formulation of suggestions for the improvement of the information management system.

This framework will support the process of reducing inefficiencies, by firstly providing a way to transparently visualise them (highlighted by asterisks in the map in section 4.3). Secondly, by analysing the current-state and through the iterative discussion on potential improvement objectives to apply.

4.1. Understanding the context

The first step consists in understanding the context and the social environment of LTC and PBC, through the interpretation of their activities and the interactions of the key stakeholders of both organisations at the beginning of the scope change process, i.e. when the information about the change needs to be communicated. This first step entails a rigorous data collection from multiple sources, as in (Shih et al. 2012), and the immersion in the social setting for an extended period of time, as in (Wickramatillake et al. 2007). Secondary data (e.g. business documents) and primary data (preliminary, informal, unstructured, scoping interviews and participation to meetings) have been collected and analysed to guarantee a detailed initial understanding of the situation. Onsite observation and extensive field notes also provided a rich background for the interpretation of subsequently collected data and information.

As introduced in section 1, the large-scale case study that is investigated in this research consists of the design, manufacturing, testing and delivery of a complex and bespoke machine for the nuclear decommissioning industry, composed by more than 30,000 components. These components are organised in composite modules, costing several million of £, and the project lead-time, i.e. the time between the placement of the order from LTC and its delivery, stretches over more than two decades.

4.2. Data collection and validation

The data collection for the creation of the current-state integrates the information previously collected through around ten semi-structured interviews. To perform the semi-structured interviews, personnel working both in PBC and in LTC were identified. These individuals were selected from different functions, since they play different roles in the communication process and have a different impression on its efficiency. The main roles engaged from both organisations were the programme manager, the project managers, the head of commercial and the responsible engineers. The project control manager, the commercial controller and the quantity surveyors were also involved, mainly for a validation purpose. However, interorganisational relationships also occur between the subunits of the two organisations or between individuals at lower hierarchical level (Oliver 1990) and these individuals (e.g. engineers) could discuss and agree scope changes, sometimes without sharing this information to the delegate authority at the commercial level. This is graphically presented in Figure 2: indeed, in theory, the changes discussed among engineers should be reported to the commercial controller that would raise the topic through official channels and in written form, to the commercial controller of the other party. However, in practice, this resulted not to be always the case, which generates misunderstandings and frustration.

Semi-structured interviews were planned, following the structure described in (Cadle, Paul, and Turner 2010), i.e. introduction and scene-setting, main questioning, thanks and explanation of 'where next'. Due to the nature of the investigation, most of the questions were open questions. Closed question were asked mainly with probing purposes, i.e. only to clarify specific points that the interviewees were raising. The interviewees were informed about the objective of the investigation and granted anonymisation. The interviews were not recorded to let the interviewees express their honest perspective on the quality of the information flow between LTC and PBC, and their emotions related to it.

The questions used in the semi-structured interviews were:

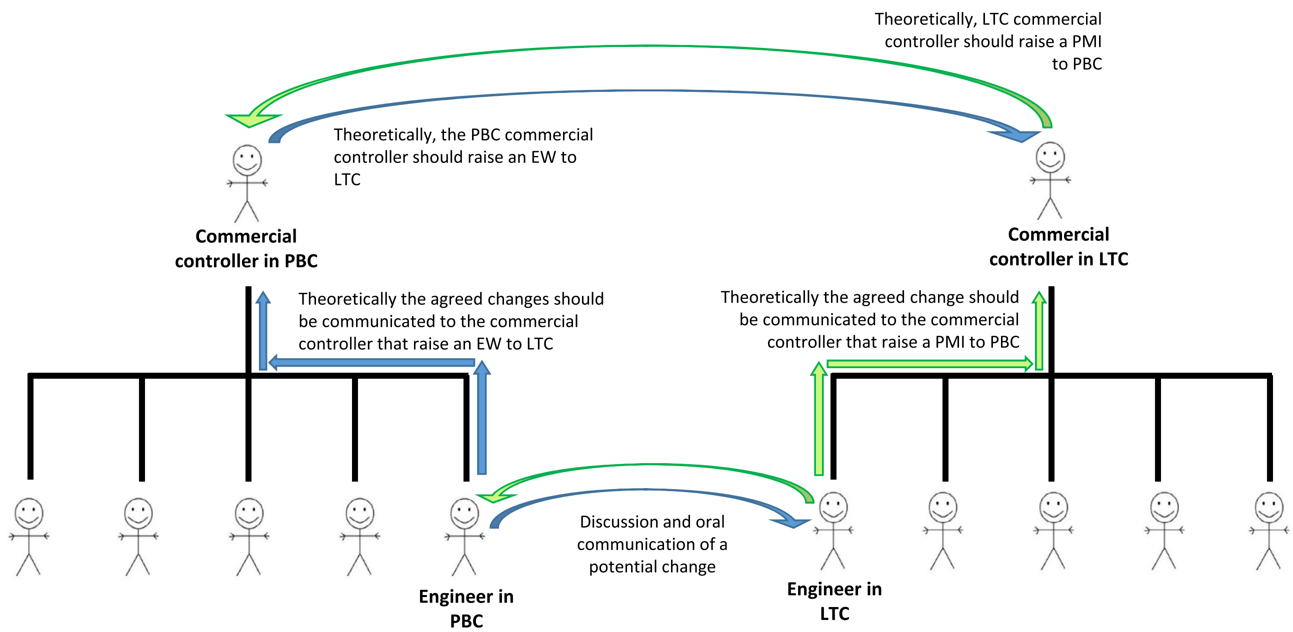

Figure 2. Scope changes agreed among engineers are not always clearly communicated to the commercial level.

- How do LTC and PBC communicate scope changes?
- Are there written and agreed procedures in place?
- How do you think that the procedures for communicating scope change work?
- Who is responsible for the different steps of the communication regarding scope changes?

The semi-structured interviewees allowed the creation of the current-state, described in section 4.3. The creation of the map of the current-state resulted was an iterative process, as its delineation was progressively refined by the different stakeholders involved. Indeed, all the interviewees were asked at least twice to check the completeness of the visual map, which was also a way to cross-validate its correctness.

4.3. Creation of the current-state

The first objective of a lean thinking is '*to eliminate non-value-added activities, also known as waste or Muda*' (Bevilacqua, Ciarapica, and Paciarotti 2015). Nevertheless, due to its scarce tangibility, it is challenging to measure the performance of the information flow and how this both is affected and affects changes. However, as one project manager in PBC mentioned during an interview: '*process inefficiencies cause frustration among people from both organizations and…this affects the client-contractor relationship!*' The graphical expression of the current-state addresses the issue of the limited visibility of the overall communication process and helps to collect and highlight the points of frustration that are caused by operational inefficiencies of both organisations.

The creation of the current-state is an interactive and iterative process that was validated through cross-checks, such as follow-up meetings with interviewees. This was necessary especially because not all the interviewees have a complete overview of the information flow process, and, as one engineer pointed out '*we just deal with the engineering bit … that's our job! We do not deal with the commercial stuff…*'.

The current-state of the case of LTC and PBC is presented in Figure 3 and Figure 4 in the form of a map, as advocated by (Bevilacqua, Ciarapica, and Paciarotti 2015; Lewis 2001; Nurcan et al. 2006) and draws from the process approach (ISO 2015). The creation of the current-state is extremely powerful for visually represent less tangible 'frustration point'. The authors were therefore very careful in the systematic recording of all the weak signals of stakeholders' discomfort (e.g. explicit complaints, repetitive negative comments on how the information flow could be optimised, etc.). Then the overall information flow to communicate changes was mapped and these weak signals of stakeholders' discomfort encapsulated in the graphical representations of the information flow. We also asked the different interviewees to cross-check the current-state map for validation purposes. Similarly to Das et al. (2007), asterisks highlight operational inefficiencies that cause frustration (white asterisks in Figure 3 and Figure 4) and actual negative risks, such are the actual possibility that the information about scope changes is not communicated to the other party (red asterisks). White asterisks underline weak signals of stakeholders' discomfort (i.e. frustration points), caused by:

- The complexity of the information flow process about scope changes;
- The use of unofficial routes to communicate the potential change;
- The lack of understanding of the impact of avoiding to use official routes due to the limited visibility of the overall process;
- The limited clarity regarding the delegated authorities;
- The limited clarity regarding the communication of priorities regarding changes;
- The long time elapsed in answering a communication from the other party.

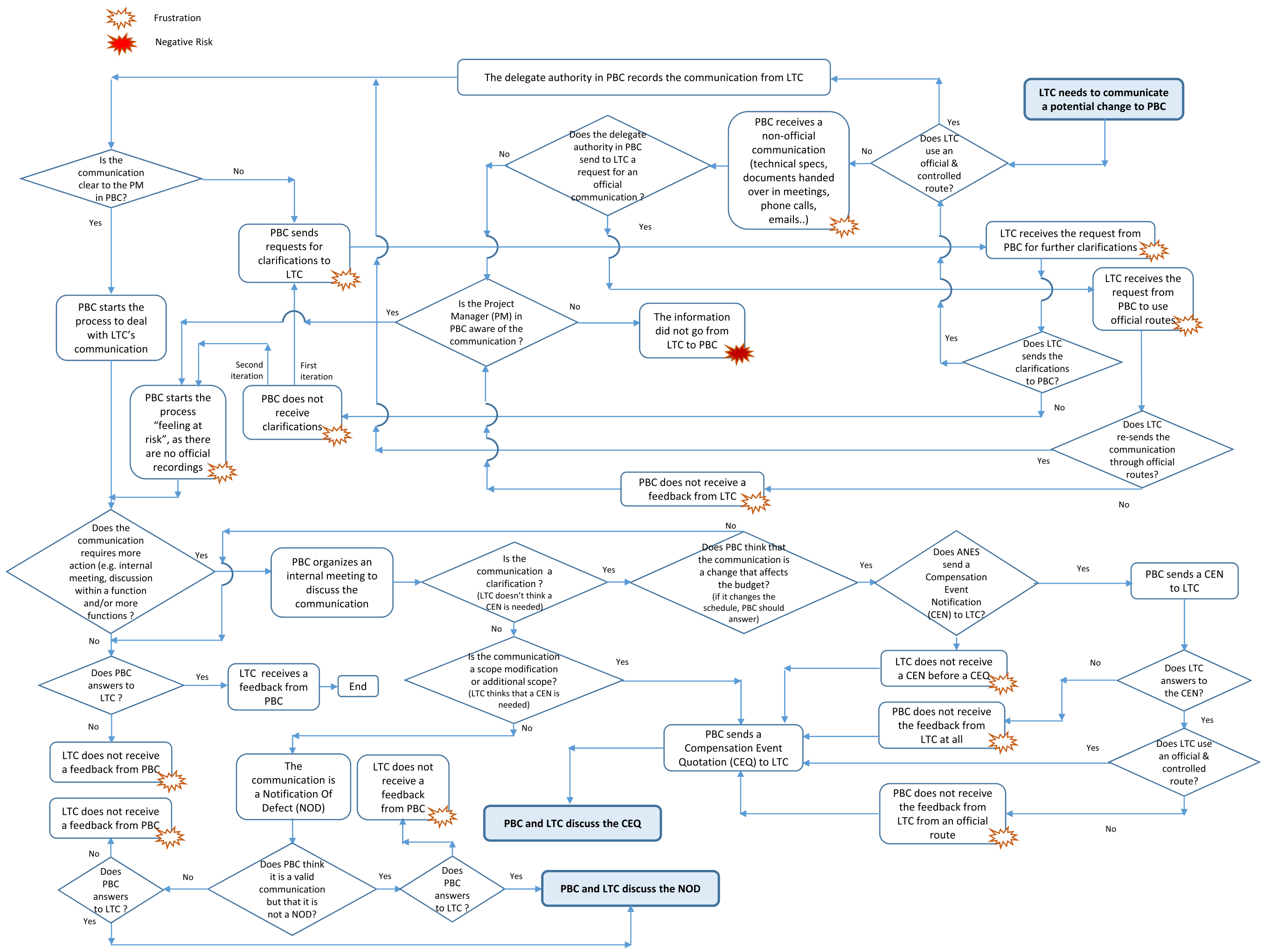

Figure 3. Information flow between LTC and PBC, when LTC has to communicate a potential change to PBC.

Figure 3 represents the current-state of the information flow when LTC needs to communicate a potential change to PBC, while Figure 4 represents the information flow when PBC needs to communicate a potential change to LTC. As it can be noticed from these two figures, frustration occurs when the communication is not efficient, and it is necessary to re-iterate the process before the complete information about scope changes is actually conveyed to the other party. This inefficiency not only cause a sense of dissatisfaction or annoyance, but also remarkably increases the overall lead time.

4.4. *Analysis of the current-state*

As introduced in section 2.2, according to (Hicks 2007), there are several causes of waste regarding information management, i.e. (i) information that cannot flow because it has not been generated, (ii) information flow that cannot be identified, (iii) excessive information is generated and most appropriate information becomes hard to be identified, and (iv) inaccurate information flow resulting in inappropriate downstream activities, corrective action or verification. These causes give raise to four types of waste, called failure demand, flow demand, flow excess and flawed flow (Bevilacqua, Ciarapica, and Paciarotti 2015). Of the four waste categories, the analysis of the current-state of PBC and LTC detects wastes and inefficiencies connected mainly to:

- flow excess, as too much information was shared between individuals at different levels of the hierarchy and not always discussed between the hierarchical levels. This, as suggested by Brookes et al. (2007) can lead to decision-making becoming more time-consuming, as hoards of information are of little value (Alavi and Leidner 2001). Hölttä et al. (2010, 1462) stress '*people in organizations are often faced with information overflow. Still, they do not seem to have access to all the information they need* as well;
- flow demand, as information is normally generated but the information exchange is hindered by the limited agreement and clarity of the formal procedures that both parties should follow in terms of identification, recording and transmission of the information by all the different stakeholders involved;
- flawed flow, as the accuracy of the information exchanged is lower than expected (e.g. information exchanged during meetings, but not sent through the official routes and/or information sent through official routes, but not subject to formal check and validation before).

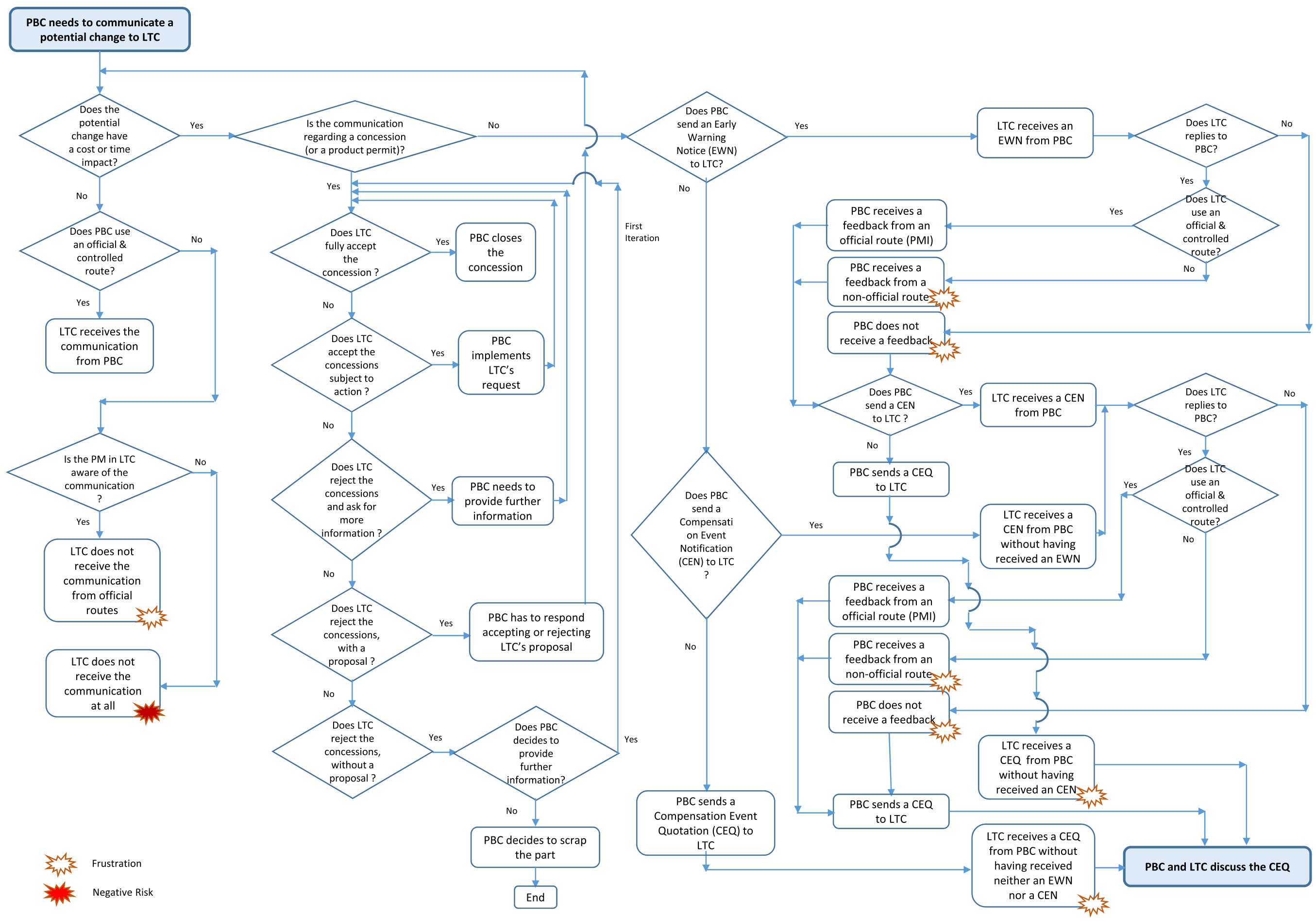

Figure 4. Information flow between LTC and PBC, when PBC has to communicate a potential change to LTC.

The rigorous identification of these inefficiencies allows the development of improvement objectives.

4.5. Development of improvement objectives

The improvement objectives stem from the implementation of steps 4.3 and 4.4. The majority of the improvement objectives that are proposed below, were suggested by one (or more) interviewee, and were subsequently presented to the other stakeholders, who were free to give their opinion on the effectiveness of the proposed solution and/or provide their own advice. The remaining improvement objectives derive from the literature on previously analysed case studies and were discussed with the interviewees in follow-up interviews. The types of intervention proposed include both formal and informal changes in the organisation. Some can be applied in the short term with limited effort, sometimes called 'quick win', while others require longer time and more effort to be implemented, as presented in Table 3.

Meetings and discussions to increase the visibility of the overall process (informal, short-term change) might include discussion to periodically revise and clarify the procedures and official routes to be used both within and between PBC and LTC, e.g.:

- Early Warnings (EWs) should be promoted, even if they do not address recurrence (Meng 2014), they are effective for problem-solving;
- a communication in a meeting should be followed by an official Project Management Instruction (PMI);
- a Compensation Event Notification (CEN) should be anticipated by a Compensation Event Quotation (CEQ);
- the answer should be communicated to the other party as soon as possible, ideally within 10 working days, as in the NEC3 best practice (NEC 2017). Indeed, even if the NEC3 contract is not formally adopted, it is important to attempt to encourage people to communicate and cooperate in order to resolve disagreement as early as possible (Meng 2014), to manage disputes (Thompson, Vorster, and Groton 2000) and to manage early, timely and proactively the arising challenges.

The application of Building Information Modelling (BIM) (a formal, long-term change) can also be considered, as it increases the visibility of the change process, clarify the individual delegated to officially require the change and optimise the communication of changes between the parties, through dynamic graphical support. However, advantages of BIM have to be balanced with the risks and the drawbacks of implementing BIM (Barlish and Sullivan 2012; Bryde, Broquetas, and Volm 2013; Kivits and Furneaux 2013). Information and communication technology can support the development and operations management of lean supply networks by providing the enabling infrastructure required (Adamides et al. 2017). However, it is important to stress the fact that '*technology alone seldom represents a competitive*

Table 3. Formal and Informal changes proposed to improve the communication flow, to be implemented in different time period.

	Improvement objectives applicable in the short term	Improvement objectives applicable in the long term
Formal Changes	• The establishment and communication of clear delegate authorities in every step of the information flow process, approved by both parties involved • The establishment of a formal check before the information is send to the other party • The establishment of a system to define, highlight and monitor the actual priorities. For example, an inter-organisational IT infrastructure may support the constant flow of knowledge between two organisations (Roldán Bravo, Lloréns Montes, and Ruiz Moreno 2017). Also, inserting a screening team could be considered, especially when the number of the change request becomes significant (Steffens, Martinsuo, and Artto 2007)	• The establishment of an advanced dynamic system, supported by IT, to highlight the time elapsed since the last communication and an early feedback system to communicate and record the reason for the delay (e.g. a 'traffic light system', or a whiteboard system as suggested by (Hölttä et al. 2010), or the application of Building Information Modelling (BIM) • The revision of the current process to manage and communicate Engineering Changes (ECs) and the establishment of a standardised one. Indeed, '*A standardized EC process must define tasks, responsibilities, rules of performance, and schedules. A standardized EC process should include answers at least to questions relating to information exchange, such as when and to whom the informing of ECs is done; who is responsible for transferring data from one IT system to another; who is responsible for informing suppliers about ECs; what templates must be used with ECs and how (e.g. EC request and EC order); and what is filled in on change information forms*' (Hölttä et al. 2010, 1643) • The establishment of an 'Enterprise Requirements Information Management (eRIM)', as suggested by (Jallow et al. 2008)
Informal Changes	• The setting up of meetings to increase the visibility of the overall process, to highlight the commercial impact of decisions taken at a lower level of the hierarchy, e.g. engineers agreeing scope changes without reporting it to the commercial level	• The clarification of the nature of the information flow (i.e. pooled, sequential, reciprocal or iterative (Whinch 2010, 209) • The establishment of a periodic regular meetings to discuss new issues arising in time

advantage' and that '*adding technology to a fundamentally flawed information management organization will do little to help and may even retard performance*' (Hölttä et al. 2010, 1463).

Both formal and informal changes address the waste highlighted in section 4.4. Indeed, by applying these changes:

- information would be generated and shared in a systematic way;
- information about changes would be clustered according to their priority;
- the accuracy of the information would be enhanced.

5. Discussion

Several relevant themes intersect in this research, i.e. (i) the efficiency of project-based companies involved in (ii) long-term relationships with their strategic client and (iii) the management of the information flow (iv) regarding the scope changes to be communicated to the other party. Individually, these topics have been vastly investigated by the literature, but only few studies of project-based companies have addressed the impact of the supply chain relationships on the project performance in construction (Meng 2012). However, the '*likelihood of poor performance such as time delays, cost overruns and quality defects usually increases step by step following the deterioration of supply chain relationships*' (Meng 2012, 193), so these relationships require due consideration.

The focus of this paper is the information flow regarding scope changes, and stems from the stakeholders' frustration and discontent that were expressed repeatedly by both PBC and LTC. What results from this analysis, however, is not applicable only to PBC and LTC, but it is also generalisable to other industries designing and manufacturing complex products. This is the case, for instance, of the aerospace and naval industry, and of companies developing customised piece of equipment (e.g. robotics) which are involved in a long-term relationship with their strategic client(s). The five-step framework could therefore act as a guideline to visually represent the company's current-state and to highlight and address operational inefficiencies.

A similar approach was undertaken by Bevilacqua, Ciarapica, and Paciarotti (2015), but limitedly to the automotive industry, where processes are overall more repetitive and standardised. Conversely, in a project-based company, non-repetitive operations are a daily occurrence, and also the information flow is less predictable, which generates reworks, delays and extra costs. Therefore, the information flow would need to be optimised, especially if the number of changes required by the clients and/or highlighted by the contractor to address omissions or errors become numerous and keep escalating, ultimately increasing the complexity of the final product itself.

Therefore, a comprehensive project change management system that also acknowledges the need of a transparent and optimised information flow is necessary. When the information about the scope change is shared with the other party, the process to manage it, can start. Ibbs, Wong, and Kwak (2001), for instance, present a change management system founded on five principle: (1) promote a balanced change culture; (2) recognise change; (3) evaluate change; (4) implement change; and (5) continuously improve from lessons learned. Continuous improvement is particularly significant, also bearing in mind that knowledge must be constantly and consistently re-created, and that the transfer from individual to collective learning is not always straightforward (Love et al. 2015). In the context of this research, this translates into the understanding that the successful implementation of improvement objectives has to lay upon a company-wide understanding of the current-state (which suffers from inefficiencies) and the collective willingness to apply and monitor these improvement objectives.

Regarding the implementation of the five-step framework, the first step to undertake is the understanding of the context and the delimitation of the research boundaries (i.e. the frustration caused by the sub-optimised information flow regarding scope changes). However, this might be hindered by several factors, starting from the openness of the company to welcome an 'external expert' (here, one of the authors) bringing his/her 'outside view', and the willingness of the interviewees to openly share both their experience and emotions. Also, the 'external expert' has to be granted a certain freedom in the selection of the interviewees, which should be conducted in an informal and relaxed environment favouring openness and intellectual honesty. In particular, it is better if the interviewees are not 'suggested' by the higher hierarchical ranks of the companies involved, but carefully selected according to their job description, expertise, frankness and willingness to participate in the research. Ultimately, the project-based companies (here, PBC and LTC) should be interested in identifying time-consuming non-value-added activities and keen to discuss improvement objectives.

Another challenge in the implementation of this five-step framework is related to the difficulty in identifying frustration and other 'weak signals' of stakeholders' discomfort caused by non-value-added activities in the information flow. Love et al. (2010) investigate claims and disputes, and identify the main causes triggering these disputes: (i) for clients, the failure to detail and correct errors or to oblige for contractual requirements and (ii) for contractors, unforeseen scope changes. Ju, Ding, and Skibniewski (2017) explore strategies to eliminate interface conflicts that affect the project effectiveness in complex supply chains, with multidisciplinary participants and a limited interest in the holistic project performance. Unlike claims and conflicts, frustration and other 'weak signals', such as anger and powerlessness, have been less investigated. This is probably due to the fact that 'weak signals' and their causes (i.e. process inefficiencies, which translates in practice into avoidable costs) are harder to both identify and quantify.

Overall, scope changes and the communication regarding scope changes, are topic that raise great interest, not only in organisations involved in the decommissioning industry (Locatelli 2018). Mello, Strandhagen, and Alfnes (2015), for example, recently explored the factors that affect coordination in engineer-to-order supply chain, highlighting change orders and the communication effort spent to address these changes as one of the factor impacting on the lead time. Tam, Shen, and Kong (2011) analyse what affect the project performance of a multi-layer supply chain focusing not only on the 'standard' iron-triangle of time-cost-quality but also exploring the performance of communication and coordination, such as delays in communicating decision, increasing communication errors when increasing layers of subcontractors, poor or lack of communication, etc. This paper also fits in the stream of research, highlighting the inefficiencies of the information flow regarding scope changes between PBC and LTC.

6. Conclusions and future research

The process of communicating scope changes between contractors and long-term strategic clients can be lengthy and complex, which can hinder the timely reaction from both parties while addressing scope changes themselves. Indeed, scope changes and the communication about these changes can be a thorny topic. One exemplary case is presented by Steffens, Martinsuo, and Artto (2007), where '*project team members had purposefully started to avoid making change requests because of the bureaucracy of the change management system*' (Steffens, Martinsuo, and Artto 2007, 709).

This paper investigates two research questions:

> RQ 1: To what extent should and could weak signals of stakeholders' discomfort be used to highlight operational inefficiencies on the information flow associated to high transaction costs?

> RQ 2: How can communication and information management be improved to address the stakeholders' discomfort, optimise the information flow and ultimately increase the overall project performance?

To answer these questions a five-step framework has been developed and applied on the real case of PBC and LTC. These five steps consist of (1) understanding of the context, (2) data collection and validation, (3) creation of the current-state, (4) analysis of the current-state and (5) development of improvement objectives.

The development of the first three steps and their application on the specific case of PBC and LTC enabled the authors to address RQ 1. Indeed, the visual representation of the current-state of the information flow highlighted several frustration points, scattered all over the map of the current-state. Remarkably, these 'frustration points' were highlighted not only by one interviewee, but have been independently stressed during several different interviews, by stakeholders occupying different working positions, and in both companies. This primarily highlights how strong the dissatisfaction caused by the operational inefficiencies in the communication of scope changes was, but also indirectly corroborates the findings regarding the operational inefficiencies. Indeed, the hypothesis that frustration is triggered by operational inefficiencies is well founded, once the boundaries of the study (i.e. the information flow about scope changes) are explained and the frustration arisen due to personal reasons (e.g. disputes with colleagues) elided. In this situation, the 'remaining frustration points' are those related with the operational inefficiencies and can therefore be used as indicators of non-value-added operations. The elimination of these non-value-added operations could optimise the communication between PBC and LTC and consequently reduces the corresponding transaction costs.

Conversely, the last two steps (i.e. the analysis of the current-state and the suggested improvement objectives) address RQ 2, as the analysis of frustration points can be used to bring out suboptimal process and foster the organisation to investigate the causes underlying the stakeholders' frustration. The optimisation of the communication flow and the reduction of the stakeholders' discomfort come therefore 'hand in hand', as tackling the causes is a way of eliminating negative consequences. Indeed, the gap analysis provides the basis for defining the actions to be taken in order to improve the current situation and 'move' towards a more efficient one. For the case of PBC and LTC, these are imputable mostly to three of the four types of waste in information management described by (Hicks 2007) and reported in Table 1, i.e. flow excess, flow demand and flawed flow. Failure demand was less emphasised by the interviewees. Section 4.5 proposes improvement objectives that could be applied to optimise the information flow between PBC and LTC, clustering them into formal and informal ones and highlighting the different timeframe that their application would require. Indeed, '*the role of information technology is not only to organise data into useful information, but also to enable the transformation of personal information into newly-created organisational knowledge*' (Adamides et al. 2017, 37) so the cost and benefits of implementing longer term, formal changes would need to be carefully evaluated.

The main limitations of this research are related to (i) the implementation of the five-step framework and (ii) the implementation of the improvement objectives proposed, which can trigger follow-up research questions.

Regarding (i), it has to be underlined that the 'outside view' provided by the external person inserted in the company is essential, as it could guarantee impartiality during both the data collection, and the creation and analysis of the current-state. Consequently, if possible, the authors recommend to rely on the 'outside view' during the implementation of the five-step framework. This could be a limitation as it could take long, for the company, to find an adequate candidate, and, for the candidate, to understand the company-specific situation (e.g. 3–4 months). Also, the presence of a 'new figure' in the company might cause some resistance among the employees, as he/she might be seen as 'an invader', and other employees might not be willing to share their experience with him/her. Nevertheless, the 'outside view' is the only practical way to deliver an unbiased analysis.

Concerning (ii), the selection between the improvement objectives proposed and their implementation have not been analysed in this paper, and could be subject of future work. Also, it could be interesting to anticipate the eventual resistance to the implementation of the improvement objectives and to investigate the best way to monitor the overall project performance. Lastly, future work could analyse to what extent 'co-creation' (e.g. as discussed by Romero and Molina 2011) could be used to effectively limit scope changes. Indeed, scope changes are a big challenge for project-based companies, and an efficient information flow is the first step to better manage them. Therefore, from a methodological point of view, this paper paves the way to a number of future research on knowledge transfer across-projects (for project-based industries) as well as in daily operations (for operations-based industries).

The practical implications of this research for both project-based and operations-based industries are profound. The five-stage process described in this research is only partially dependent on the project-based or operations-based nature of the organisation, which suggests that it may be used with success in both environments. However, this research also suggests that the ability to implement a lean approach depends, in part, upon the ability of practitioners to detect 'weak signals' and be able to include or simulate an 'outside view' when redesigning information flow. Both of these are 'soft issues' that concern the 'informal organization'. The social nature of information and knowledge management has long been acknowledged (Brookes et al. 2006): the challenges in designing management systems and inculcating management cultures that recognise this situation is still lagging. The research in this paper highlights to practitioners the need to develop approaches that do not rely only on formal management systems but also to develop their own emotional intelligence.

Notes

1. Exact queries: 'transaction cost'; 'lean management'; 'lean information management'; 'information management'; 'scope change'.
2. Exact queries: 'transaction cost' AND 'information management'; 'information management' AND 'scope change'.

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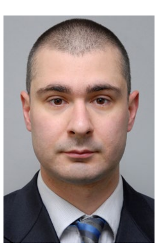

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Publication VI

"Applying value management when it seems that there is no value to be managed: the case of nuclear decommissioning"

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Applying value management when it seems that there is no value to be managed: the case of nuclear decommissioning

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Abstract

The vast majority of project management literature relating to infrastructure focuses on the project lifecycle up to commissioning and handover. Conversely, little attention has been paid to the end-of-life of infrastructure, i.e. when decommissioning begins. Infrastructure decommissioning projects are long and complex projects, involving an extensive network of stakeholders. Moreover, their budgets can reach hundreds of billions of Euros and, for many of these projects, keep increasing. Since decommissioning projects do not generate direct revenues, they are often considered an expensive nuisance with limited value linked to their delivery. This paper explores the use of Value Management (VM), examining the constraints of decommissioning projects and the requirements for successful implementation of VM, focusing on the nuclear industry due to its techno-socio-economic relevance. Findings derived from the application of content analysis on semi-structured interviews with experienced decommissioning practitioners include suggestions on how to implement VM, ultimately contributing to increase the knowledge on how to deliver decommissioning projects with better performance.

Keywords: Value management; Infrastructure end-of-life; Nuclear decommissioning; Megaproject; Social challenges

1. Introduction

The majority of project management research has investigated the planning, design and delivery of construction projects and megaprojects (Pitsis et al., 2018; Locatelli et al., 2017; Lindhart and Larsen, 2016; Tripathi and Jha, 2018), and only limited and recent attention has been given to the end-of-life of infrastructure (Invernizzi et al., 2018a). Decommissioning, dismantling and removal refer to the end-of-life of infrastructure and to the process of withdrawing it from service, "clean" it and deconstructing it. For instance, in the nuclear industry, decommissioning is defined as *"all the administrative and technical actions taken to allow the removal of some or all the regulatory controls from a facility [...]"* (IAEA, 2006, P.31–32). For the sake of synthesis and simplicity, in this paper, the authors will use the word "decommissioning" to embrace all the terms mentioned above.

Infrastructure decommissioning projects and programmes can be long, complex, and reach costs of billions of Euros, e.g. for oil & gas and nuclear facilities (Oil and Gas UK, 2017b; NDA, 2017b). As an example, in the UK' Continental Shelf , the decommissioning cost estimates reach a staggering £60bn (Oil and Gas Authority, 2017), while the estimates for decommissioning the UK nuclear legacy are at £229 billion (NDA, 2018).

Moreover, decommissioning projects involve an extensive network of stakeholders, including client(s), contractors and subcontractors, the managing organization, the government, regulators, employees and the local community (Perko et al., 2017; Love, 2012; IAEA, 2009, 2008). Moreover, the number of completed decommissioning projects are extremely small compared to the number of facilities that have actually been

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built. For instance, globally, more than 500 nuclear power plants have been built, but only 16 have been fully decommissioned (OECD/NEA, 2016). Similarly, 470 offshore oil & gas installations (HM Government, 2013) have been built in the North Sea, but only "*around 10% of oil and gas platforms installed across the North Sea have been decommissioned and less than 5% of pipelines*" (Oil and Gas UK, 2017a, p.12). Additionally, several other types of complex infrastructure (such as chemical plants and large dams, as well as low carbon energy infrastructure such as wind farms) are now coming to the end of their useful operational life and will soon need to be decommissioned. Chemical plants need to be properly decommissioned to avoid the risk of leakages into the environment, and to free land that can be reused, which is becoming a pressing issue especially in densely populated countries such as in Western Europe; dams need to be decommissioned because the concrete that makes up their structures is degrading, and this combined with the pressure from the soil accumulated in the dam during the operational life of the infrastructure may pose an unacceptable risk.

These decommissioning projects have common characteristics that differentiate them from more traditional construction endeavours. Indeed, at the completion of these projects (Invernizzi et al., 2017, 2019):

- ➢ there is no or little cash in-flow;
- ➢ no revenue generating assets are created;
- ➢ no "landmark infrastructure" is built, but instead, the site is often left with "nothing" and its use remains restricted for several years;
- ➢ there is no "red ribbon" to cut for politicians
- ➢ jobs are often lost.

These characteristics pose severe socio-economic challenges as many of the traditional incentives to deliver projects effectively and efficiently are simply not there.

Moreover, infrastructure decommissioning is often perceived as "dull" and uninspiring aiming at getting rid of and dispose of infrastructure that was once valuable. The reality, however, is dramatically different: decommissioning projects can be complex projects that encompass several interrelated valuable activities, such as hazard reduction, safety and security guarantees, site remediation and restoration (OECD/NEA, 2014b; Laraia, 2012). More specifically, decommissioning not only allows the safe and secure handling of hazardous material, but also allows to free space on a licensed nuclear site which could then be utilised for new nuclear. Additionally, under the umbrella-term of "decommissioning", construction projects such as the building of facilities for handling, treating and storing of waste may be required. Considerable R&D may also have to be carried out to ensure that the best technologies are developed and the best possible solutions are implemented in decommissioning projects (OECD/NEA, 2014a). Nevertheless, despite the decommissioning industry being rich in valuable projects, how to "value manage" end-of-life of infrastructure is still remarkably under-investigated. Even with the challenges associated with decommissioning, the effort that decommissioning projects require, and the limited current knowledge on how to manage these projects, the majority of academic papers on decommissioning simply take a "hard science" perspective (investigating chemical, physical, radiological aspects), and how to actually address the project management challenges of decommissioning projects (in order to deliver valuable projects) seem to be largely disregarded by academics.[1]

Value Management (VM) is a philosophy and management style to enhance stakeholders' decision making which is operationalised through a series of studies during the project life cycle (Kelly et al., 2015). VM is able to reconcile differences in views between key stakeholders, promoting early debate in the process of selection and delivery of the best solution, and it is particularly useful when dealing with long and complex projects (Kelly et al., 2015). Male et al. (2007) describe VM as a team-based, process-driven methodology that uses function analysis to examine and deliver a product, service or project in the best possible way, combining whole life performance and cost, without compromising quality. Function analysis "*is argued to be the only distinguishing characteristics of value management from other philosophies or approaches*" (Male et al., 2007, p.109). However, even if VM can support the planning and delivery of decommissioning projects, this topic also seems to be overlooked by the academic community.[2]

This paper fills this knowledge gap by exploring the potential role of VM in decommissioning. More specifically, this paper answers the following research questions:

- ➢ what does "value" mean in the context of decommissioning?
- ➢ What are the constraints that affect decommissioning projects that can be addressed with VM?
- ➢ What are the requirements for a successful implementation of VM in decommissioning projects?

Addressing these research questions ultimately supports the development of knowledge on how to deliver decommissioning projects with improved performance.

This exploratory research focuses on the nuclear decommissioning industry, due to its economic relevance, the urgency to deal efficiently with radioactive material arising from the decommissioning activities, and the availability of information (e.g. reports published by international organizations such as the International Atomic Energy Agency, (IAEA,

[1] The search in Scopus of academic papers on the topic of nuclear decommissioning reveals 445 papers (as in November 2018), but only two papers have been published in "project management journals", i. e. one in the International Journal of Project Management and one in the International Journal of Managing Projects in Business (exact query in Scopus: "nuclear decommissioning").

[2] The search in Scopus of academic papers on the topic of value management in projects (as in November 2018) reveals 341 papers (exact query in Scopus: "value management" AND "project" AND NOT "earned"). The search is limited to "decommissioning projects", does not show a single publically available result (exact query in Scopus: "value management" AND "project" AND "decommissioning" AND NOT "earned").

2016a, 2011), the OECD/Nuclear Energy Agency (OECD/NEA, 2016, 2012), etc.).

Moreover, the urgency to investigate decommissioning is due to the fast-growing number of nuclear facilities that are approaching their end-of-life and will soon need to be decommissioned, as well as the costs that this will involve.[3] Since the vast majority of nuclear facilities in Europe are owned by their respective Governments, this burden is on the tax payers' shoulders. Therefore, how to "value manage" these projects and improve the ratio of "benefits vs costs" in nuclear decommissioning projects is a critical and pressing issue.

To achieve the above-mentioned research questions, Section 2 explores the literature on value and VM, and reviews the requirements for the successful implementation of VM on construction. Section 3 explains the selection of the focus of this research, also describing the data collection and analysis. Section 4 presents the research findings, which are then discussed in Section 5. Section 6 highlights the limitations and provides suggestions for future research, and Section 7 concludes the paper.

2. Theoretical background on value and value management

2.1. The complexity of defining "value"

Defining what "value" is can be troublesome as "*value is a subjective term and is manifested in different ways such as attitude, belief, desire, preference, need and criteria*" (Leung and Liu, 2001, p.11). Value also has a dynamic nature which changes and evolves over time (Aliakbarlou et al., 2017). Thyssen et al. (2010) discuss value both in objective and subjective terms, also differentiating between intrinsic and extrinsic value. Cha and O'Connor (2005) argue that there is no single definition of value, as value is an abstract concept in nature. In the realm of projects, discussions about value deal with outputs (at the end of the project), outcome (some months after the project), and impact (years after the project) that a project delivered according to different stakeholders, levels and timescales (Turner and Zolin, 2012; Zwikael and Smyrk, 2012; Davis, 2014).

This brief review highlights that agreeing what value is for construction projects is subjective and is often an open question that is difficult to answer. Moreover, when dealing with the infrastructure end-of-life, answering the question "what is value?" is even harder than when dealing with construction projects in general. Indeed, for instance, for nuclear decommissioning projects, "value" is derived from the interplay of moral, ethical, social, economic and environmental aspects, underpinning the need to ultimately restore the nuclear site, which often has a very restricted use.

In the VM literature, value is often defined through the ratio between functional performance the and the cost of resources (eg. (Hayles et al., 2010)), or the relationship between benefits and costs (Laursen and Svejvig, 2016). Luo et al. (2011, p.1003) quoting (Green, 1992) argue that VM is concerned with defining "*what 'value' means to a client within a particular project context by bringing the project stakeholders together and producing a clear statement of the project's objectives*". This highlights that "value" in construction industry projects can potentially be described through an agreed statement.

2.2. The value management study

VM is a robust mechanism to balance societal, environmental and economic aspects as well as to assist decision-making with the aim to maximise the functional value of a project and eliminating unnecessary costs (Abidin and Pasquire, 2007). VM supports key stakeholders, such as the client(s), the main contractor(s) and the project owner, in considering the challenges surrounding the specific project they are involved in. This includes agreeing on a mission statement to be used as a benchmark for future decision making (utilising function analysis) and analysing all the options available to the project team, considering the political, social, economic and environmental impacts (Hayles et al., 2010, p.45). Even if the terms "VM", "value engineering" "value analysis" are sometimes used interchangeably (Cha and O'Connor, 2005; Fong et al., 2001), some authors differentiate between these terms, arguing that "value analysis" and "value engineering" have been developed to optimize projects and processes, while VM focuses on the overall achievement of "value" (Laursen and Svejvig, 2016).

A VM study can be split into three main phases (Lin et al., 2011):

1. A preparation phase, also called "orientation and diagnostic phase" (Male et al., 2007);
2. A workshop phase, where normally selected stakeholders will gather, discuss and ultimately produce a report and an action plan to ensure solutions are implemented. This phase can be divided into six sub-phases: information, function analysis, creativity, evaluation, development, and presentation (Hwang et al., 2015; Lin et al., 2011);
3. A post-workshop phase (sometimes called the "implementation" phase), in which the actions decided upon in the workshop phase will be delivered (Lin et al., 2011).

Several management processes exist to apply the knowledge required to effectively manage projects, being a process a "*set of interrelated actions and activities performed to create a pre-specified product, service, or result*" (PMBOK, 2013, p.47). In the construction industry, several VM processes have been identified, 44 of which have been categorized by Cha and O'Connor (2005) according to their context of application. Remarkably, none of the VM processes of the ones presented by (Cha and O'Connor, 2005) refers specifically to the end-of-life of a project and to decommissioning projects. This shows, once again, the lack of attention posed on decommissioning, as

[3] World Nuclear Association official website: http://www.world-nuclear.org/press/briefings/decommissioning-costs-in-context.aspx [Accessed August 21, 2018].

Table 1
Requirements for successful implementation of VM studies in the construction industry.

Requirement for successful implementation of VM in the construction industry	
Overall consensus on the VM study and approach	- Agreement to participate to by all parties invited to the value study (Kelly et al., 2015, p.28) - Senior management support (Kelly et al., 2015, p.28) - Top management commitment and support (Hwang et al., 2015, p.5) - Good involvement of project stakeholders (Hwang et al., 2015, p.5) - Support from government sector (Hwang et al., 2015, p.5) - Education on VM (Hwang et al., 2015, p.5) - Communication and interaction among participants (Hwang et al., 2015, p.5) - Commitment of the stakeholders involved in the VM study (Male et al., 2007, p.108) - Participation and interaction (Shen et al., 2004, p.211) - Client support and active participation (Shen and Liu, 2003, p.487) - Management support and approval (Fong et al., 2001, p.312)
VM team	- Appropriate team skill mix (Kelly et al., 2015, p.28) - The presence of client decision taker (Kelly et al., 2015, p.28) - Appropriate resource allocation (Hwang et al., 2015, p.5) - Clear responsibilities and roles (Hwang et al., 2015, p.5) - Having experienced participants with decision making authorities "*who can engage constructively then and there*" (Thyssen et al., 2010, p.28) - Multidisciplinary composition of the VM team (Shen and Liu, 2003, p.487) - Project team formation (Fong et al., 2001)
VM study leader	- An experienced and independent value study leader (Kelly et al., 2015, p.28) - The way in which the total process is facilitated (Male et al., 2007, p.108) - Qualified VM facilitator (Shen and Liu, 2003, p.487) - facilitator's efficiency in gathering information (Fong et al., 2001)
VM objective(s)	- Clear and unambiguous objectives of VM (Hwang et al., 2015, p.5) - Clear objectives of the VM study (Shen and Liu, 2003, p.487) - VM enables the participants to set their goals (especially for critical tasks) and derive suitable solutions to fulfil the clients' requirement (Leung et al., 2002, p.68)
VM environment and time	- An isolated workshop environment (Kelly et al., 2015, p.28) - Sufficient time to conduct the evaluation analysis, as "ideas produced in the creative phase require extensive consultations and in-depth investigations", which is time-consuming (Shen et al., 2004, p.212).
Other requirements of the VM study	- Appropriate risk allocation and management (Hwang et al., 2015, p.5) - Innovation and critical thinking (Hwang et al., 2015, p.5) - Appropriate value job plan (Hwang et al., 2015, p.5) - The methodology employed (Male et al., 2007) p.108 - Budget setting (Fong et al., 2001, p.312) - Solution generated within the time limit (number of ideas and number of feasible ideas, cost or value of the ideas) (Fong et al., 2001, p.312) - etc.

well as the need to investigate which of the categorized VM processes are applicable to decommissioning projects as well.

2.3. The requirements for successful value management in construction projects

Kelly et al. (2015, p.28) list the prerequisites to ensure the smooth running of a VM study. These include:

- ➢ Agreement to participate by all parties involved in the study;
- ➢ Senior management support for the VM;
- ➢ An experienced and independent VM study leader;
- ➢ An appropriate team skill mix;
- ➢ An isolated workshop environment.

Other authors have elaborated on this list. For example, Hwang et al. (2015, p.5) classify 11 "success factors" of a VM study, including communication and interaction among participants, clear and unambiguous objectives of VM, and education on VM. Shen and Liu (2003), identify 23 critical success factors and grouped them into factors that are relevant for (i) the preparation phase, (ii) the VM workshop, (iii) the implementation of the generated proposals and (iv) other supporting factors. The four factors that showed the highest ranking were:

- ➢ Client support and active participation;
- ➢ Clear objectives of the VM study;
- ➢ Multidisciplinary composition of the VM team, which "*can be regarded as the most crucial requirement for the VM team*" (Shen and Liu, 2003, p.489);
- ➢ A qualified VM facilitator;

Table 1 provides a summary of the requirements for successful implementation of VM, as highlighted by academics investigating the construction industry. However, the literature also highlights the difficulties surrounding how to measure the performance of VM studies (see for example (Lin and Shen, 2007)).

2.4. Value management in decommissioning projects

The lack of academic publications relating to VM in decommissioning (see note in Section 1) might be due to the widespread belief that there is limited value associated with decommissioning activities and that decommissioning is simply about dismantling and dealing with waste. Not only it is more difficult to define what the value of a decommissioning project is, but often there is also a lack of clarity about what is regarded as an actual "asset" and what is regarded as "waste". For example, assets can be defined as "*possessions of value, both real and financial",* and real assets include" *land, buildings or machinery owned"* (Black, 2003, p.15). So, considering a building on a nuclear site that is not in use anymore, is this building considered an asset (as it could provide the benefits to store nuclear material or equipment) or is it simply a legacy that needs to be dismantled? And again: is the land where the building is located an asset or a liability (as it might be contaminated and might require further work before being re-used)? Similar is the case of spent fuel, which consists of fuel that can be re-used (after special and expensive treatment) for future nuclear-related operations. Is this an asset or is it waste that needs to be disposed of? These are only a few of the many examples of ongoing debates within the industry where the line between what constitutes an asset and what constitutes waste is blurry. Ultimately, the definition of the value of an asset in the decommissioning industry embraces several interrelated aspects, such as health and safety, security, environmental aspects, etc., hence its value is not merely defined through its financial value.

This leads to further difficulties concerning how to "value manage" a decommissioning project.

3. Method

3.1. Selection of the unit of analysis

This paper focuses on the case of value managing the nuclear decommissioning of Sellafield[4] (in the UK) due to a number of reasons. First of all, the UK has to deal with the largest European nuclear legacy together with the associated decommissioning challenges (NDA, 2017b; Öko-Institut, 2013), and Sellafield is the largest UK (and European) nuclear site undergoing decommissioning, both regarding the physical land that it occupies and the techno-socio-economic effort that it requires. Indeed, Sellafield hosts around 1400 buildings, of which 240 are nuclear facilities (NAO, 2015), concentrated on a 6 km^2 site (NDA, 2017b), and its decommissioning plan incorporate several interrelated activities including reprocessing spent fuel from nuclear reactors, retrieving and packaging waste from existing storage facilities, treating radioactive waste, transferring waste to repositories and disposal facilities, demolishing buildings, and clearing the final site (NAO, 2018, p.31). Hence, Sellafield is an exemplary case to investigate.

Secondly, Sellafield's decommissioning is estimated to take some 120 years and more than £160 billion to decommission Sellafield (i.e. around 70% of the total estimates of decommissioning the whole UK nuclear legacy, currently estimated at £229 billion (NDA, 2018). These figures stimulate debate not only on the overall costs of this endeavour, but also on project temporality (Brookes et al., 2017). In fact, Sellafield's decommissioning taking more than 120 years, overturn the classical dichotomy of project management of projects being "temporary" and the organizations delivering the projects being "permanent" (with 120 years the project will be luckily to outlive the organizations). Hence, Sellafield is a representative case to research VM in decommissioning, as actions undertaken to ensure that Sellafield decommissioning is managed to deliver value have an impact that extend in a long time period and affecting a number of stakeholders.

Thirdly, Sellafield is owned by the UK Nuclear Decommissioning Authority (NDA), which is a non-departmental public body created through the Energy Act in 2004 (UK Government, 2004). In 2016, the NDA published "the NDA value framework" (NDA, 2016). This document is a reference providing guidelines for value managing decommissioning projects, and its publication shows the NDA's understanding on the need to focus on the delivery of value to stakeholders, in terms of a number of interrelated subjects (including health and safety, security, environment, etc.). Therefore, being the NDA the owner and directly involved with Sellafield's decommissioning, the decision to focus on Sellafield is reasonable.

Lastly, pragmatically, the authors have over the years built a network of stakeholders from Sellafield Ltd., the NDA, other UK government-owned and operated nuclear services technology providers and key Sellafield contractors, who are willing to collaborate in the development of the current research and were willing to be interviewed as part of the data collection process.

The decommissioning of Sellafield is highly complex, time-consuming, extremely difficult to manage, and it involves a multitude of stakeholders. Consequently, the whole decommissioning of this site could be regarded as a "troll" project. i.e. as a creature that is difficult to tame and control (as defined by Klakegg et al. (2016, p.283)), and is, therefore, an exemplary case to focus on.

The analysis of Sellafield's decommissioning is performed using semi-structured interviews with experienced practitioners. The data collection and analysis is explained in the following sections.

3.2. Data collection

This research started with a preliminary literature review and non-structured discussion with decommissioning experts to identify the extent to which VM has been applied in the nuclear decommissioning industry. This was followed by a systematic review of the literature on VM in construction projects, and the selection of the method to collect and analyse primary data.

The collection of primary data was performed using semi-structured interviews (DiCicco-bloom and Crabtree, 2006) involving participants selected through purposive sampling

[4] For a more detailed description of Sellafield, please refer to Sellafield's official website: https://www.gov.uk/government/organisations/sellafield-ltd [Accessed August 22, 2018], and to the official publications by the UK national Audit Office (e.g.(NAO, 2018)) and the UK Nuclear Decommissioning Authority (e.g. (NDA, 2017a)).

(Palinkas et al., 2015). Interviewees were selected among senior employees of Sellafield Ltd. (i.e. the organization managing Sellafield site), of the NDA (i.e. the organization that owns the site), of the Nuclear National Laboratory, as well as of key Sellafield contractors. A total of 26 interviews were conducted between January 2018 and March 2018, corresponding to a total of 27 participants, as two participants preferred to be interviewed at the same time. Twenty-four interviewees have more than 10 years of experience in the industry. Eleven interviewees are employed by Sellafield Ltd., five by the NDA, seven by the Nuclear National Laboratory, while four interviewees are major Sellafield contractors. The suggested length of each interview was 30 min, but 2 interviews lasted almost an hour, which was due to the eagerness of some of the interviewees to provide more detailed answers. On average, interviews lasted 25 min.

The data collection followed a two-step process. First of all, five preliminary interviews were conducted with two key stakeholders from Sellafield Ltd., one from the NDA and two interviewees from major contractors to gain a more detailed understanding of the research context. The following questions were used as a basis for the dialogue:

➢ How would you define "value" in the context of decommissioning projects?
➢ How would you define "value management" in the context of decommissioning projects?
➢ According to your experience, what are the major constraints and bottlenecks that affect the performance of decommissioning projects?
➢ What do you think are the most relevant drivers and barriers to the implementation of value management in decommissioning projects?
➢ Can you describe an example of a decommissioning project where value management was implemented and has been successful and one example in which value management was implemented, but it was not successful?

Following the first five interviews and a preliminary analysis of the information collected, the authors performed 21 additional interviews, also adding the following questions to the questionnaire:

➢ Which stakeholders are (usually) involved in value management studies?
➢ How is the performance of a value management study assessed?
➢ How is the "NDA value framework" implemented in practice?

The questionnaire was sent to the respondents at the same time as the invitation to participate in the research. The respondents were not required to answer the questions in a written form, but they were given the possibility to read the questions in advance and gather relevant information. In this way, the interviewees were also able to have time to decide if they wanted to participate in the research or not. All the interviewees were granted anonymization.

3.3. Data analysis

After permission for recording was granted, the interviews were recorded, and the conversation transcribed. Then, the transcribed material was systematically analysed through content analysis (Hsieh and Shannon, 2005; Dixon-Woods et al., 2005).

Content analysis is "*a research method for subjective interpretation of the content of text data through the systematic classification process of coding and identifying themes or patterns*" (Hsieh and Shannon, 2005, p.1278). Advantages of content analysis include the fact that it is transparent, unobstructive and flexible, as it can be applied to a variety of information (Bryman and Bell, 2007, p.318). Qualitative content analysis aims to preserve the advantages of quantitative content analysis by applying, at the same time, a more qualitative text interpretation (Kohlbacher, 2006).

Of the three main approaches of content analysis (i.e. the conventional one, the directed one and the summative one (Hsieh and Shannon, 2005)), the conventional approach is used in this research as pre-existing theories are limited. Coding is achieved through an iterative and mostly inductive process of analysing the information, following (DeCuir-gu and Mcculloch, 2011; Elo and Kyngäs, 2008; Mclellan-Lemal and Macqueen, 2003). Hence, the transcribed material was reviewed, and a first impression noted. Then, relevant pieces of the transcript weres labelled to allow a preliminary coding. Discussion with colleague followed, and the coding was iteratively finalized.

Table 2 summarizes the example of how the code ultimately named of "Unknowns and uncertainties about the site conditions and the consequent need of (additional) characterization[5]" was derived. As exemplified in Table 2, the knowledge of the interviewer and transcriber (i.e. one of the authors) was fundamental to understand the relationship underlying the fact that the so-called "unknowns" hinder the site condition, and the fact this is directly related to the need of additional analysis of the site before proceeding with a more detailed planning how to proceed with the decommissioning.

4. Findings

4.1. "Value" and "value management" in the decommissioning industry

From the interviews it emerged that a unique definition of the meaning of "value" and "VM" in decommissioning projects is not agreed upon. Ten out of 26 interviews broadly described "value" and "VM" in decommissioning as respectively the "hazard and risk reduction" and "being efficient and effective" in managing that hazard and risk reduction. However, other

[5] Where "characterization" in the nuclear industry refers to the determination of the nature and activity of radionuclides present in a specified place (IAEA, 2006, p.18).

Table 2
Example of the coding and abstraction process.

Extracts from the interviews	Preliminary coding and identification of sub category	Final coding
- *"Knowing what you got in in the first instance! We are a very risk adverse organization […]. Sellafield has a complex range of buildings, from the ones that stopped operating in the late fifties, to those that stopped operating later this year, the level of knowledge of those facilities…is low!"* - *"Lack of information of what the problem is, physical constraints in terms of the ability to get in/look at the building, quite a lot of conservatism, quite frequently, about selection of technology, but also understanding which safety cases you are going to put together."* - *"Not knowing because the records were not absolutely precise or… there were no records at all!"*	Unknowns and uncertainties about the site conditions	Unknowns and uncertainties about the site conditions and consequent need of (additional) characterization
- *"Then characterization is a problem: what are the characteristics of the site, and how to get there"* - *"It's the initial characterization of the material…is one of the biggest issue we have"* - *"…and if the facility was sitting idle? It might have deteriorated!"*	Need of additional analysis of the condition of the site to be performed through characterization	

themes were mentioned, such as the need to meet the stakeholders current and future needs, and the need to address the topic of intergenerational justice, which refers to the fact that the benefit of past and present nuclear generations are mainly for the present generations, while the burdens of dealing with long-lasting radioactive material is transferred to future generations (Taebi et al., 2012).

Only two interviewees explicitly and clearly described VM as a structured three-phase process and/or including a systematic function analysis with the ultimate objective of agreeing on the selection of a preferred option. "Brainstorming exercise" or "optioneering meeting" were used as synonyms of VM, as these were all broadly described as meetings requiring (i) a preparation phase (where preliminary data and information are collected), (ii) a workshop phase (where different options are evaluated), and (iii) an implementation phase (where the agreed preferred option is carried forward and eventually implemented). Indeed, the usage of different terminology ("brainstorming exercise" vs. "optioneering meeting" vs. "VM intervention") highlights that interviewees have different views on the ultimate goal of (i) collecting information, (ii) attending a meeting and (iii) discussing options.

For example, the focus of an "optioneering meeting" was described mostly as the collection of different technical solutions, and it is likely therefore that an evaluation of the actual value (in terms of benefits vs costs, and not simply of the technical benefits) would be overlooked. Additionally, naming "a VM process" using the word "meeting" suggests that VM participants are neglecting the importance of the preparation phase, which is pivotal (as it is in cost estimation (Torp and Klakegg, 2016)). Moreover, the usage of different terminology may also be an indicator of a lack of clarity surrounding the objectives of VM studies.

4.2. Constraints of decommissioning projects and the potential role of VM

The interviewees emphasized a number of constraints that affect decommissioning projects. These, according to the interviewees, often hinder the delivery of such projects. Table 3 organizes the coded constraints according to their frequency of occurrence, limiting the list to the constraints that have been highlighted during at least three interviews. The potential role of VM in decommissioning as derived by the researchers' analysis of the information collected is in the next sections.

Included in the findings of Table 3, is the fact that more than half of the interviewees highlighted that "unknowns and uncertainties" about the site conditions are one of the major challenges that hinders the smooth progress of decommissioning, as it requires multiple characterization campaigns (where "characterization" in the nuclear industry refers to the determination of the nature and activity of radionuclides present in a specified place (IAEA, 2006, p.18)). Known unknowns and unknown unknowns have been extensively discussed in the project management literature (Ramasesh and Browning, 2014, p.190). These are defined respectively as "*uncertainties of which the PM [project manager] is aware and to which the techniques of conventional risk and opportunity management can be applied*" and "*Unrecognized uncertainties of which the PM is unaware"* (Ramasesh and Browning, 2014, p.190). In nuclear decommissioning, "known-unknowns" and "unknown-unknowns" are (somewhat ironically) a well-known challenge (see for example (IAEA, 2016b; Öko-Institut, 2013; IAEA/OCED-NEA, 2017)). Unknowns and uncertainties are likely to also be a challenge in decommissioning projects outside the nuclear industry, as after decades of operation, it is likely that certain records will be difficult to find, have not been updated, and that tacit knowledge of operators of the plants have been lost (e.g. due to retirement). In this situation, VM supports a systematic and structured collection of information, and a discussion of the existing knowledge among stakeholders. Moreover, a VM workshop provides a forum for discussion among stakeholders on how to best address uncertainties and lack of information.

Similarly, the second-most emphasized constraint, i.e. "social-related challenges", e.g. in terms of "people's mind-

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Table 3
Constraints of decommissioning projects and how VM can tackle these constraints.

Constraints of decommissioning projects	Extracts from the interviews that highlight constraints and bottlenecks of decommissioning	The potential role of VM in decommissioning, as derived by the researchers' analysis of the information collected from the semi-structured interviews
Unknowns and uncertainties about the site conditions and consequent need of (additional) characterization	- *"Knowing what you got in in the first instance! We are a very risk adverse organization […]. Sellafield has a complex range of buildings, from the ones that stopped operating in the late fifties, to those that stopped operating later this year, the level of knowledge of those facilities…is low!"* - *"Lack of information of what the problem is, physical constraints in terms of the ability to get in/look at the building, quite a lot of conservatism, quite frequently, about selection of technology, but also understanding which safety cases you are going to put together."* - *"Not knowing because the records were not absolutely precise or…there were no records at all!"* - *"…and if the facility was sitting idle? It might have deteriorated!"* - *"Then characterization is a problem: what are the characteristics of the site, and how to get there"* - *"It's the initial characterization of the material…is one of the biggest issue we have"*	VM can support a systematic and structured collection of information, and a discussion of the existing knowledge among stakeholders. Moreover, a VM workshop can provide a place for discussion by the stakeholders on how to address uncertainties and lack of information. Characterization refers to the determination of the nature and activity of radionuclides present in a specified place (IAEA, 2006, p.18). A VM study could support the analysis of the extent of characterization that is required and how it should be progressed
Social-related challenges (e.g. people's mind-set)	- *"You need the bigger picture, to get collaboration, to get momentum…too many people do not have the bigger picture"* - *"In decommissioning, there is no motivation. Which are the drivers? The only drivers are the saving…than it is better to sit and wait!"* - *"By bottlenecks you mean constraints? I know what you mean. It is…what I would say is: the main bottlenecks in decommissioning project is the people. It's the people! And again…it's a mindset, it's a culture, it's unnecessarily constraints, it's being blanked with processes and procedures. It's people wanting to use something they want instead what they need..!"* - *"Sites are 'set in their way', 'this is how we do this'! So: it's about the mindset and the about the system. They have their system, and if you want to change it…they would not want."*	The first step to promote change in people's mind-set is to understand where the issues lay and how employees could be motivated, e.g. through clear objectives, incentives, etc. Collaboration and buy-in can be achieved by including the key stakeholders (early) in the decision-making process, i.e. through a VM study.
Unavailability of stable funding	- *"Annualized funding! It's a problem since when the NDA arrived. If you are doing really well, you have no funding to continue, until next year. This takes away all the benefits…because you have to de-mobilise the team. The team might not be ready on the first of April. Maybe they went on another project, and even the learning curve is lost. Accelerating…if the money is there!"* - *"Put all the right pots of money in place, make sure that it can actually move forward into delivery"*	VM cannot deliver an increase in funding, or more stability in terms of the funding. However, through a structured discussion on the value and costs of activities, it may be possible to optimize available resources, e.g. through systematic resource management.
Unavailability of a reliable supply chain and suitably qualified resources when needed	- *"So it's a quite narrow market! There's certain amount of place in the market, and they still have to charge a price, and whatever that price might be… that could actually end up being the price…no other options!"* - *"Even when they get a number of tenders, for example, for a project, you know, it's a small number, there is only a certain number with the capability to deliver some of these things as well"* - *"There is often difficulty in finding the right suitable qualified experienced resource to the workplace, at the time you want them to be at the workplace"*	The VM study, especially if applied early in the project life-cycle, could highlight potential skills shortages and market constraints, and could also support better planning.
Regulatory challenges	- *"I think there is almost a myth around the regulatory environment, that is used almost as an excuse"* - *"Regulatory compliance? Yes, transport regulations, waste acceptance criteria…manager that operate the plant might not understand + they don't know what are the options..such as do not generate the waste in the first*	According to a number of interviewees some of the regulations are not well understood, and this might cause unnecessary over-engineering. The inclusion of all the key stakeholders, and (if/when possible) regulatory representatives as well, could be critical to improving value.

Table 3 (*continued*)

Constraints of decommissioning projects	Extracts from the interviews that highlight constraints and bottlenecks of decommissioning	The potential role of VM in decommissioning, as derived by the researchers' analysis of the information collected from the semi-structured interviews
	place! Minimize, compact, incinerate, etc.*, separate high and low radioactive waste. And BAT assessment."* - *"Now, I would never forget the head of the regulator stood up in front of 200 of us, [among] regulators and Sellafield employees and he quoted a lot of the regulations […]. He says 'as far as reasonably practicable', and he went through a number of regulations that quoted 'as far as it's practicable' …and said: 'so what I find on your site is that a lot of people are trying to build that gold-plated Rolls-Royce before you can actually start retrieval…but well actually, when you are looking at the regulations, when you are looking at that, you are probably breaking the law, because you should get to it quicker, because the risk is so high! You should be getting into that quicker and finding a flexible mean of doing that"* - "*…there are bottlenecks when it comes to sanction and funding" […]* - *"We do have at the moment a lack of signing off things which holds projects up"*	
Knowledge and information management	- *"From the inception of an idea, you do the same kind of things, but it's…*" *we want to do this", you know, "we want to do that", but nobody tend to go around what is the real value of doing it in the first place. It's almost a given that there is a demand, you know what I mean? We do not question that demand too much"* - *"We do silo-work"* - *"Everyone sees its part of the jigsaw"*	VM can support knowledge and information sharing between stakeholders involved in different projects/ activities. A VM workshop is also an excellent vehicle in itself to improve communication, foster team building and collaboration.
Lack of clarity in the scope definition	- *"Communications of the benefits that we actually want, so clarity of what the scope is, those are the two major ones for me"* - *"the project management and the client have had different understanding of what the project scope should actually be..[…] there was a mismatch between delivery to the client and that has to be resolved"* - *"The customer does not understand what is required to get the waste off the plant to the disposal site. So, we work as intermediary! "*	One of the main benefits of a VM study is that it can provide clarity in terms of the definition of the project scope, specifically, through the use of function analysis.
Lack of clear waste routes and availability of storage and disposal facilities	- *"I was used to work on radioactive waste inventories and […] there is an awful number of waste streams, waste that we have across the site, that we shuffled away in corners or in facilities and we don't have a recognized route for treating them"* - "*Constraints of decommissioning? Lack of disposal routes! You cannot dismantle a Magnox now…there is no point if you don't have an ultimate destination…you don't know where to put the waste"*	VM can support a systematic and structured collection of information, and can help to highlight which are the actual challenges that hinder the progress of decommissioning.
Poor planning	- *"Better planning! More assessment of the risks. Everyone wants to start with the project…and there is a risk to miss opportunities"* - *"..and then poor planning. We do have at the moment a lack of signing off things which holds projects up, we also have difficulty in procurement, that is a bottleneck, and again, the upfront planning would be to prevent the bottle neck"*	One of the main benefits that a VM study can provide is improving project planning, by promoting discussion on the "way forward" from the conceptual stage of the projects as well as at regular intervals during the project's life cycle.
Interface between decommissioning and waste management	- *"connecting the dots between the project team and the waste management team, the decommissioning team and* etc. etc. *it would have had a much more aligned and cost effective solution!"* - *[discussing a construction project to enable decommissioning] "the fact that these people [radioactive waste management people] were missing was*	A VM study could promote a better understanding of the interface between a decommissioning project and waste management operations.

(*continued on next page*)

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Table 3 (*continued*)

Constraints of decommissioning projects	Extracts from the interviews that highlight constraints and bottlenecks of decommissioning	The potential role of VM in decommissioning, as derived by the researchers' analysis of the information collected from the semi-structured interviews
	reflected by the fact that they didn't know about the packages!"	
Over-engineering	- *"The regulator are, and the procedures we have on our side, I believe, good regulations! And good procedures! It's how they are applied. They need to be applied intelligently […]. They have been written by very intelligent and clever people who when they set certain criteria in the regulations that people have to meet, they have included a degree of margin in their assessment for the regulation. So, you've already got margin built in the regulations,* per se*, built in by intelligent people. So, taking the regulations and putting some more extra margin and more extra margin and extra margin to the engineering side of things…they end up being a way a way over engineered compared to what the need to do. The things is they need to go down to meet the regulations and you don't have to go anything more than meet the regulation. "*	Over-engineering could be avoided if every stakeholder has a clear understanding of the inputs and outputs of each task, and the VM study can help in addressing this issue.
Lack of space on site	- *"so you have got to safely build a facility, that facility has to be ready as we tear a building down, firstly if you are taking a building down, you have to make sure that there is the space for the material"* - *"but then you have no space for decommissioning? If you de-licence, you would not have space to store your waste, because you don't have the agreement with the Environmental Agency to store where it's de-licensed..."*	The space available cannot change with a VM study, but (similar to funding), the usage of the space available could be optimized.
Contractual and procurement agreement	- *"Customers have limited understanding of the NEC3 contract. It's a construction contract. And people struggle to understand it properly. With early warnings? They get very defensive […]. Contracting options are not selected properly by the customer. So, if the customers have already an idea, they might not have considered different options."*	The discussion around which are the best contractual arrangements during a VM workshop could support better decision making.

set", can be tackled with the help of VM. Indeed, the first step to promote change in people's mind-set is to understand where the issues lay and how employees can be motivated, e.g. through clear objectives, incentives, etc. Thus, collaboration and buy-in can be achieved by including the key stakeholders early in the decision-making process, for example through a VM study which could both tackle social challenges at both at a "macro-level" (Invernizzi et al., 2017) and a "micro-level" (Invernizzi et al., 2018b).

Conversely, not all the constraints highlighted during the interviews can be addressed directly through VM, which is the case of the "unavailability of stable funding", of a "reliable supply chain and suitably qualified resources", as well as of "regulatory challenges". However, through a structured VM discussion on the value and costs of each activity, it may be possible to optimize available resources, highlight potential skills shortages as well as regulatory constraints, and therefore guarantee better planning.

Indeed, "poor planning" has been explicitly mentioned during five interviews, and it is strictly linked with other constraints mentioned by the interviewees and listed in Table 3, e.g. the "lack of clarity in the scope definition". Scope definition is both driven and drives decisions about characterization, and it needs to include considerations regarding the "interface between decommissioning and waste management", in order to avoid "over-engineering" and re-work (also mentioned during five interviews).

Lastly, the following constraints have been mentioned in less than three interviews and therefore not included in Table 3. Two interviewees mentioned (i) the overall difficulty to gain new technology buy-in and highlighted that (ii) the overall conservatism that is widespread in the industry, which (combined) negatively affect the possible introduction of new technologies. One interviewee raised concerns regarding the lack of thinking about decommissioning already during the design of the nuclear facilities. These challenges can only be very limitedly addressed through VM at this stage of the project.

The key takeaway from Table 3 is that the majority of the constraints highlighted by the interviewee with decommissioning practitioners can benefit from VM studies, as VM can tackle the lack of communication and limited information sharing that affect decommissioning projects. VM can also provide a forum to discuss and make explicit project scope as well as improve project planning, especially when considering the complex interfaces that exist between decommissioning projects and waste management operations.

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Table 3 also shows that the majority of these constraints, although particularly relevant in decommissioning, are not unique to decommissioning projects. In fact, constraints such as the uncertainties that exist in the earlier stages of a project, social-related challenges, and the availability of stable funding, are common to construction projects in general (and especially relevant to large ones).

Conversely, some constraints are more specific to decommissioning projects, such as the challenges caused by poor knowledge management or the lack of information regarding previous operations of the infrastructure (which might have lasted decades). Lastly, some constraints are exclusive to *nuclear* decommissioning projects, such as the complex interfaces between nuclear decommissioning projects and waste management operations, and the lack of disposal routes for nuclear material and nuclear waste, which are challenges that do not affect the non-nuclear industry.

4.3. Requirements for successful implementation of VM in decommissioning projects

The interviewees showed overall less congruence in answering the question regarding the requirement for successful implementation of VM in decommissioning, than when answering the question about the constraints of decommissioning. However, as discussed below, the answers provided by the interviewees were in overall accordance with the formalized requirements concerning the successful implementation of VM in construction presented in Table 1. This denotes that most of the requirements that have been highlighted in the literature as relevant for the successful application of VM to construction projects are relevant for decommissioning projects as well.

For example, the successful application of VM requires that consensus regarding the need of a VM intervention is shared among all the participants. During the interviews, one interviewee explained: "*once I did a workshop in which optioneering did not get the answer that people had expected, and people would say...then we selected the wrong criteria! Because this is the wrong answer!"*. This exemplifies how participants' consent, agreement and active participation has to be reached at the early stage of the VM study and, when possible, starting with a "partnering workshop" (Thyssen et al., 2010) to elicit the stakeholders' opinions. Indeed, *"projects that set off with the best intentions can often incur set-backs when there is not a shared understanding at the outset, when the desires of one stakeholder are not reciprocated, when the environmental issues are not balanced with the economic issues or the politics are at odds with social issues"* (Hayles et al., 2010, p.49). These challenges need to be recognized to get everyone on the same page from the start, and avoid starting with a solution and then making all the data fit that solution.

Moreover, the VM process should be systematically structured, and as one interviewee explained: *"It cannot be a "free for all conversation"! People have to buy in the approach, they have to accept their role! It's important to gain agreement for the criteria to evaluate options, and also on the weight of certain factors! Everyone one has different ideas of these criteria and weights. And if the criteria are not well-defined, you need to find agreement! Also, having sufficient time is important. This is enabling!"*

Additionally, having a multidisciplinary composition of the VM team is particularly important for decommissioning projects, and this emerged to be particularly relevant in the nuclear industry, where the number and variety of stakeholders are high. Therefore it is important to identify the key stakeholders with appropriate decision making authority, during the various stages of the decommissioning project lifecycle. A stakeholder mapping exercise could support this selection. The need of many stakeholders participating in the workshop could considerably increase the cost of a VM study. However, compared to the overall effort of nuclear decommissioning projects (as exemplified by Sellafield case), the total cost of additional and/or more comprehensive VM studies would be negligible, and would most likely be outweighed by the additional value that VM could provide.

During this study, interviewees stressed particularly the fact that regulators should be invited to participate to VM studies, because, even if they cannot provide a definitive go/no-go answer, they can still challenge the workshop participants, stimulate critical thinking and provide a relevant contribution. Sharing his personal experience on this topic, one interviewee stated: "*I will never forget when the head of the regulator stood up in front of 200 of us, [including] regulators and Sellafield employees and he quoted a lot of the regulations […]. He said 'as far as reasonably practicable', and he went through a number of regulations that quoted 'as far as it's practicable' … and said: 'So what I find on your site is that a lot of people are trying to build that gold-plated Rolls-Royce before you can actually start retrieval…but well actually, when you are looking at the regulations, when you are looking at that, you are probably breaking the law, because you should get to it quicker, because the risk is so high! You should be getting into that quicker and finding flexible means of doing that"*. It can be therefore argued that regulators could provide a relevant contribution, even if their comments during the VM workshop are not necessarily binding. Indeed, regulators "*ask different questions, and can give their opinion, or advice. They are very active participants and they challenge the workshop! I think they can bring a lot of value!*", as one interviewee explained.

Having "externals" to the project team can also be seen as a barrier for the success of the VM study, as the participants might feel uncomfortable to present their opinions openly, which is both an individual and cultural issue of great relevance. However, it has been argued that conflict also stimulates creativity, which can ultimately support better decision making (Hayles et al., 2010). Nevertheless, as excessive conflict can be a major hindrance to the effective operation of a team (Leung et al., 2002), the VM study leader should ensure that every participant has the appropriate time and opportunity to illustrate their points of view.

The VM study leader should also ensure that the VM study is not biased and that no pre-conceived options or pre-designed objectives are imposed. This can be very challenging, as human nature is affected by several cognitive biases (Evans et al., 1993), such as the "belief bias" which is the tendency to accept arguments that are aligned with our prior knowledge, values and beliefs, while rejecting counter arguments and the "anchoring bias", which consists of the tendency to rely heavily on the initial piece of information offered. These cognitive biases might affect VM studies. For example, two interviewees highlighted some issues during VM studies. One interviewee illustrated a situation in which "*some people put some additional constraints to block some options, because they did not like some of the outcomes. This rejected a lot of valid solutions!*", while the second one stated "… *they started half though the process! They had already got rid of all of those options somehow and now they had a set of criteria that could only lead to one solution! And during the morning, I raised a question… why are you starting from that point and not this point?' And they all looked at me as if I had just strangled a small pet! Because I said what they all knew! Because they were pushing for a certain outcome!".* This situation could be avoided by an experienced VM study leader, active participation of all the team and clear processes in place. Indeed, a key factor of a successful VM study is having a VM study leader with appropriate technical, risk management and VM experience, preferably at a senior management level in the client organization, adopting a clear process signed off by senior management. For the nuclear industry in particular, the VM study leader should not only be familiar with the VM study, but should also have enough experience to understand the socio-techno-economic challenges that characterizes the nuclear industry.

Furthermore, the objective of a VM study does not necessarily overlap with the aim of overall decommissioning projects itself. Indeed, the aim of the VM study can refer to the clarification of the project scope (at an early stage of a project) or the selection of the most appropriate procurement system (at a later stage of the project development), which are not the ultimated objective of a decommissioning project itself.

A well-structured VM environment and appropriate time-scales allocated for the VM study also plays a pivotal role. For example, one interviewee had to facilitate a one-day VM workshop where a lot of different options on how to develop a project had to be assessed, and due to (i) a lack of time and (ii) insufficient information provided by the participants, it was impossible to evaluate all the options and select a preferred one. Another highlighted *"people need time, not to make a decision in one meeting…they need time to challenge!",* while another explained *"the first calibration takes absolutely ages! And then you need to speed up. You need a facilitator that knows that and can reassure the group. It might take one hour to assess an option and you have 20 to assess in 4 hours. It does not mean you will fail! You have to tell them: "you are calibrating yourself, it's going to get faster". It's a group development of storming, brainstorming and forming!".* A VM study is not only made of a "workshop phase" but participants need to know that VM also includes a data collection phase (during which the participants need to prepare for the workshop and assemble data to identify project constraints and potential issues that might arise), and a post-workshop implementation phase both of which require additional time.

Concerning the overall VM study, VM should be implemented in the early phase of the project, where the "*early phase*" can be defined as in (Kolltveit and Grønhaug, 2004, p.547), i.e., "*the process and activities that lead to, and immediately follow, the decision to undertake feasibility studies and to execute the main project".* Moreover, VM should be implemented at regular intervals during the lifecycle of a decommissioning project, to ensure the continuous delivery of "best" value.

Especially for large projects, VM should not be advisory but compulsory, and the "option to abandon" or "the option to switch to a better solution" should be examined at each stage of the project development. As Male et al. (2007, p.113) explain, VM could be used to highlight when a project needs complete re-planning. For example, when a project team becomes dysfunctional, the VM study may prove that it is better to abandon the project using that project team.

5. Overall discussion

5.1. Response to the research questions

The research presented in this paper posited three research questions, namely:

- ➢ What does "value" mean in the context of decommissioning?
- ➢ What are the constraints that affect decommissioning projects that can be addressed with VM?
- ➢ What are the requirements for a successful implementation of VM in decommissioning projects?

Circumspection in arriving at an overall response to research questions is vital, particularly in exploratory studies like the current one. Any assessment of the degree to which this research answers these questions must be predicated mostly upon the capabilities and limitations of the research method employed, as well as upon the research context. Indeed, the research reported in this paper involved interviews with a tightly scoped sample, which is constrained by the nature of the industry investigated and the consequent difficulty in having access to information.

First of all, the response to the first research question provided by the interviewees emerged to be very ambiguous. There appears to be only a limited shared understanding of what value in decommissioning means. Furthermore, there is a substantive disparity in the milieu in which interviewees' responses are situated. Some responses are centred around on the processual nature of value management and therefore conceptualise value in terms of project "efficiency". Other responses seem far more aware of a wider societal dimension that shapes "value in decommissioning" and respond in terms of international justice and responsibility to future generations. When this lack of clarity of what value means in decommissioning is juxtaposed with the need for clarity in understanding the scope and objectives for the single VM study, it is very difficult to clearly see how any

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application of VM in a decommissioning project can guarantee project success.

Nevertheless, leveraging on the systematic collecting, coding and analysis of the constraints of decommissioning projects highlighted by the interviewees, as well as the requirements for successful implementation of VM in decommissioning (mostly derived from the literature on construction projects in Section 2.3), a way to implement VM keeping in mind the ultimate aim of improving the performance of decommissioning projects can been suggested. Indeed, the constraints (or “barriers”) facing decommissioning projects (i.e. the answer to the second research question) do appear to have the potential to be ameliorated to some degree by VM (albeit that the internal linking logic between the constraint and its potential to be addressed by VM is provided by the researchers and not by the interviewees). In fact, the requirements for a successful implementation of VM in decommissioning projects (i.e. the third research questions) appears to be very similar to the requirement for a more general application of VM, and evidence was found to suggest that the factors identified by previous research in this area would be as important in decommissioning projects as in other applications. In this study, however, the need for a multi-disciplinary team (and particularly including representatives from the regulatory bodies), of an experienced VM study leader, and a clear definition of the VM objective(s) were particularly emphasized.

To respond in summary to the research questions posed in this paper, whilst VM has the potential to tackle the constraints surrounding decommissioning projects, and existing theory is applicable to the process of VM in decommissioning per se, the current lack of shared understanding of what "value" means in decommissioning severely inhibits, if not prevents, the use of VM in the context of these kinds of projects. Hence, VM has potential to improve the performance of decommissioning projects, but in order to achieve its full potential, there is a need to have an overarching and shared definition of “value” for decommissioning projects.

5.2. Contributions to theory and practice

The research presented in this paper provides a contribution both to theory and practice.

One of the major theoretical contributions of this paper is predicated upon the context of this research, namely that of decommissioning projects. The applicability and extendibility of project theory to decommissioning projects has not been previously researched, and there is an urgent need to fill this knowledge gap not only to what concerns the nuclear industry, by also regarding the end-of-life of other energy infrastructure, given the growing importance of this type of projects, as outlined in the introduction to this paper.

The first of such contributions to theory is one of reinforcement. Indeed, the findings of existing studies that give frameworks for successful implementations of VM (captured in Table 1 of this paper) are replicated in the findings of this paper.

The second contribution to theory is derived from the identification of the constraints (or ‘barriers’) on decommissioning projects identified by interviewees. These are a useful addition to considerations of using project management approaches in different project environments such as those identified by (Hajikazemi et al., 2015; Terlizzi et al., 2016; Engström and Stehn, 2016) in other sectors.

A third theoretical contribution of this paper lies in its attempt to increase the understanding of delivering project value. The experience of the diversity of the understanding of delivering value in projects and the movement from processual and monetary conceptualizations of value towards wider and more holistic understanding is well explored by Laursen and Svejvig (2016). The research in this paper exemplifies this movement, as the interpretations of value expressed in this research range from focussed constructs of “efficiency” through to wide-ranging interpretations involving social justice. As such, they emphasise the need for some mechanism of reconciliation in constructs of value as an a priori requirement for VM. Laursen and Sverjig's call for an independent theory to support this mechanism may be provided by such developments as Porter and Kramer's ideas of “shared value” (Porter and Kramer, 2011).

A further contribution to theory refers to the conclusion that decommissioning projects need to be framed in a system lifecycle perspective, embracing both the project phase and operations, and considering the creation of value inter (and not only intra) organizations (Artto et al., 2016; Matinheikki et al., 2016). This takes this research into the analysis of decommissioning *projects* and waste management *operations,* also including the investigation of the interdependencies between decommissioning projects and of the management of the material and waste that arise during decommissioning.

Concerning the more practical contributions, the research highlights constraints relating to nuclear decommissioning projects as well as the requirement for successful VM in such projects. Hence, the results will aid project managers in their decision making, to improve organisational VM knowledge, to establish internal procedures, or to establish how VM studies should be implemented. In fact, the practical guidance on the delivery of public value is not specific to decommissioning projects. This paper, focusing on the Sellafield in the UK, references the development of a business case, through a five-case model, i.e. the strategic case, the economic case, the commercial case, the financial case and the management case (UK Government, 2015). The UK NDA tailored this guidance on decommissioning in (NDA, 2015, 2013). However, these documents do not discuss the actual implementation of VM interventions in practical terms. This paper, by first highlighting constraints that affect decommissioning projects and by discussing the requirements for successful implementation of VM, fills this gap providing a “more practical” guidance on how to implement VM.

Consequently, the findings relating to the constraints of nuclear decommissioning projects equip project managers with a list of constraints of nuclear decommissioning projects that are likely to affect nuclear decommissioning projects around the world. Moreover, the findings relating to the requirements for successful implementation of VM in nuclear decommissioning could support VM in other decommissioning projects in other industrial sectors.

6. Limitations and future research

There are some limitations that affect this research which should be addressed in future research.

The first one is that VM has been investigated as a "stand-alone" intervention on decommissioning projects, and future research could investigate the possible integration of existing processes with VM ones. For example, some attempts have been made to suggest how to integrate risk management with VM (e.g. (Dallas, 2006)). The integration between risk management and VM processes could, for example, broaden the discussion around risks (traditionally focused on strictly-technical and negative risks that might affect the projects) in order to embrace non-technical risks and market opportunities, as these might play a pivotal role during the project development.

A second limitation of this research is related to the decision to focus on a single UK nuclear decommissioning project (i.e. the case of Sellafield), and on the decision to interview only stakeholders contractually linked to this major decommissioning endeavour. Therefore, future research should seek the perspectives of external stakeholders.

Moreover, the number and length of the interviews could be seen as a limitation. However, the interviewees were selected among senior experts and who are able to convey quality information in a very short time and in a very efficient way (see also Section 3).

Additionally, follow-up research could also scrutinize the drawbacks (if any) of implementing VM in non-nuclear decommissioning projects, e.g. investigating the end-of-life of ageing infrastructure in other industrial sectors. Benchmarking VM practices applied to other industrial sectors could also provide valuable insight on how to integrate VM with existing processes concerning the selection of the best option to pursue, since VM "*in project-based organizations represents an attempt to see beyond the immediate results and a way to bring stakeholder input into defining project and program scope"* (Martinsuo and Killen, 2014, p.64).

Additionally, as in most of the literature on VM, this paper has focused primarily on the benefits of applying VM in the decommissioning industry, and limited attention has been given to the costs of VM interventions (e.g. cost and time of organizing and managing VM studies). These increased project costs (and potential lengthening of the planning phase) are deemed necessary, as there is the expectation that overall project cost will ultimately be lowered, and the schedule of the project reduced. However, future studies should focus on these, as well as on the comparison of expected VM costs vs the actual reduction of the overall cost of the project.

Lastly, future work could also include the collection of practical examples of successful and unsuccessful implementation of VM in decommissioning, e.g. through in-depth case studies.

7. Conclusion

Nuclear decommissioning projects are complex, long, expensive, and similarly to construction projects (Locatelli, 2018), they are often delivered late and over budget. Moreover, decommissioning projects involve a large number of stakeholders such as governments, regulators, managing organizations, etc., and not all of these stakeholders have the same objectives, which often hinders the decision-making process and project progress. VM is a methodology that can draw together conceptual thinking on a project as well as gather stakeholders to promote information sharing and ultimately agree on an optimal project solution.

The findings of this research show that the decommissioning project constraints that have been mostly emphasized by the interviewees embrace both constraints that are common to construction projects (e.g. the availability of stable funding), and constraints that are unique to decommissioning (e.g. the uncertainties about the site condition, such as its radiological contamination), and that the majority of these constraints can be at least partially tackled through VM. VM, however, should be carefully planned in other to achieve its full potential. Moreover, this research highlights that the requirements for successful implementation of VM in the context of decommissioning reflect the ones identified by the VM literature on construction projects, but that the need for a multi-disciplinary team (and particularly including representatives from the regulatory bodies), of an experienced VM study leader, and a clear definition of the VM objective(s) are particularly relevant in nuclear decommissioning projects. Furthermore, this research contributes to the wider aim of improving the overall performance of nuclear decommissioning projects through the appropriate selection of improvement approaches. In this respect, understanding value (and applying more formal processes of VM) has a role in improving decommissioning through its utilisation since the very beginning of the lifecycle of a nuclear programme. Hence, a holistic and societally based view of 'value' might become a requirement for future investments in the nuclear industry.

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C. Overall discussion and conclusion

This section provides a brief summary of some of the main findings of this research, discusses the contributions of the overall research to the existing body of knowledge, and underlines how each publication has contributed to achieve each of the research objective listed in section A.2. Lastly, this section discusses the overall limitations of this research and suggests future research paths.

C.1 Brief summary of some of the key findings of this research

Table 1 summarises some of the key findings of this research.

Summary of some of the key findings of this research	
Publication I	Benchmarking is suitable to identify best practices and generate ideas for improvement. However, it needs to be tailored to the specific research context. A methodology based on benchmarking that envisages both qualitative and quantitative analysis is suitable to investigate NDPs.
Publication II	Personnel transition (between operations and decommissioning) and public unacceptance are social-related challenges that hinder the progress of NDPs.
Publication III	Several interrelated NDP characteristics affect the NDP cost and time performance, including (i) uncertainties and unknowns about the site condition and the consequent need for additional characterization, (ii) the limited clarity of the waste routes and availability of storage and disposal facilities, (iii) the clarity of scope and site end-state, (iv) knowledge and information management and (v) the inexperience of project managers involved in NDPs.
Publication IV	The relationship between the operationalizable NDP characteristics that affect the NDP performance can be tested using statistical tests suitable for small sample sizes.
Publication V	Not only the content of requested scope changes, but also the communication about these scope changes between client and contractor involved in a long term relationship can hinder the overall NDP performance.
Publication VI	Value Management (VM) is a project management practice that promotes early debate and facilitate the finding and agreement of the best solution. The requirements for the successful implementation of VM in NDPs include the need of a multi-disciplinary team involved in the VM study, the need of an experienced VM study leader, and a clear definition of the VM objectives.

Table 1. Summary of some of the key findings

The application of the methodology presented in Publication I to investigate the NDP characteristics that affect the NDP performance highlighted a number of key findings. First of all, from the piece of research focusing on the social-related challenges of NDPs, personnel transition and public unacceptance emerged as two NDP characteristics able to delay the NDP progress, and even cause its complete halt. These NDP characteristics also emerged during the analysis of primary information collected by interviewing senior decommissioning practitioners performed for the research presented in Publication III, in this way reinforcing the findings of the research presented in Publication II. However, only a very small number of interviewees explicitly referred to the above-mentioned social-related challenges as the most relevant for the NDP performance. This highlights the need to share the findings of Publication II.

Alongside the above-mentioned social-related challenges, the senior practitioners interviewed for the research presented in Publication III stressed several other NDP characteristics that affect the NDP performance. These included, among others: (i) uncertainties and unknowns about the site condition and the consequent need for additional characterization, (ii) the limited clarity of the waste routes and availability of storage and disposal facilities, (iii) the clarity of scope and site end-state, (iv) knowledge and information management and (v) the inexperience of project managers involved in NDPs. Only some of these NDP characteristics have been discussed in previous publications about NDPs. Moreover, no previous publication tested statistically their relationship with the NDP performance, Stemming from the findings of Publication III, Publication IV tests the relationship between the operationalizable NDP characteristics and the NDP cost performance through statistics. However, the contribution of Publication IV is mostly methodological, due to the limited quality of the information available on the NDP costs.

Of the NDP characteristics emerging from the research presented in Publication III, the topic of scope changes, and more specifically the communication about scope changes is investigated in Publication V, which highlight how efficient information management is fundamental, especially when involved in long and complex projects. Finally, also of the NDP characteristics presented in Publication III, the topic of inexperienced project managers involved in NDPs emerged. This finding, in combination with the discussion surrounding the “value” of NDPs, triggered the research presented in Publication VI, which highlights the requirements for the successful implementation of VM in NDPs. These include the need for a multi-disciplinary team involved in the VM study, the need for an experienced VM study leader, and a clear definition of the VM objective(s). These findings provide guidelines for improving VM studies in NDPs, and ultimately to deliver NDPs with better performance.

C.2 Contribution to knowledge of this research

The research presented in this thesis is about the development and application of a methodology based on benchmarking to investigate the NDP characteristics that affect the NDP performance from the project management perspective. To achieve this aim, the author developed a methodology based on benchmarking and applied it on European NDPs. Hence, this research fits in both the methodological stream of literature leveraging benchmarking, as well as the broader literature investigating what affects the performance of projects. Additionally, this research provides a more practical contribution to managers in the nuclear decommissioning industry, by increasing the knowledge about NDPs. The following sections elaborate more in details these contributions.

C.2.1 Contribution to the research on benchmarking

The author developed a methodology based on benchmarking (see Publication I), primarily informed by Anand & Kodali (2008), El-Mashaleh et al. (2007), Costa et al. (2006), and Garnett & Pickrell (2000), who highlighted a variety of ways in which benchmarking can be implemented. The methodology developed for this research is a step forward compared to the literature on benchmarking, traditionally focused on construction projects and relying on large data sets, often not publicly available (e.g.(Luu et al. 2008; El-Mashaleh et al. 2007; Costa et al. 2006; Love & Smith 2004)). Indeed, compared to the abovementioned literature, this research formalized a methodology suitable for the investigation of the project characteristics that affect the project performance when the sample size is very small. This methodology envisages to complement qualitative and quantitative analysis (see Publication I).

Concerning the more quantitative part of this methodology, this research inherited the work by (Brookes & Locatelli 2015; Locatelli, Mikic, et al. 2017), who use a quantitative approach (i.e. the Fisher's Exact Test and machine learning) to test the relationship between project characteristics and project performance. Consequently, in this research, the quantitative part of the methodology is based on (Brookes & Locatelli 2015; Locatelli, Mikic, et al. 2017) but has also innovative elements in it. Indeed, stemming mainly from (Andres 2006; Mehta & Senchaudhuri 2003), the author identified the Barnard's test alongside the Fisher's exact test as the most suitable statistical tests to explore the NDP characteristics that affect the NDP performance, and this shows methodological progress compared to previous research which employed only the Fisher's exact test (Brookes & Locatelli 2015; Locatelli, Invernizzi, et al. 2017).

C.2.2 Contribution to the project management research

This overall research fits in the "project management school of thought" named the "*success school*" (Turner et al. 2013, p.17). Indeed, even if a number of publications have been written on the topic of "success factors" and this "*area continues to provide fertile grounds for research*" (Turner et al. 2013, p.18), the topic of decommissioning has been, until now, remarkably overlooked. Therefore, this research contributes to addressing this research gap.

Compared to construction projects (due to the construction/decommissioning dichotomy but also the number of research on construction), it also emerged that decommissioning projects lack the traditional management-related motivations to timely and effectively complete the project(s), which hinders their timely and cost-efficient completion. These motivations are related to the absence of cash-flows and positive foresights that would motivate timely project completion, such as looking forward to revenue-generation, completed landmark infrastructure and grand opening and the creation of new job position. Hence, findings from previous publications on "success" factors are only limitedly applicable to NDPs, and testing their validity on NDPs is not the aim of this research.

This overall research provides the contribution of making explicit the NDP characteristics that affect the NDP time and cost performance. This topic has, until now, partially been discussed by practitioner-based publications by international organisations, such as the IAEA and the OECD/Nuclear Energy Agency. However, these publications do not systematically collect and analyse the NDP characteristics that affect the difference between time and cost estimates and the actual time and costs, and they tend to (i) focus mostly on NDPs cost estimates (e.g.(IAEA/OCED-NEA 2017; OECD/NEA 2012; OECD/NEA 2010)), (ii) discuss costs but not time performance (e.g. (OECD/NEA 2016)), (iii) focus on a small number of European NDPs (European Court of Auditors 2016; Öko-Institut 2013), etc.

The findings from this research, therefore, build upon the aforementioned publications and highlight the NDP characteristics that affect the NDP performance according to the senior practitioners. Findings from this research highlight some NDP characteristics which were already discussed in previous publications (e.g. the need to have good knowledge of the site conditions, mentioned by the OECD/NEA (2010)), characteristics that were highlighted by early stages of this research (Invernizzi et al. 2017) (e.g. the role of a project leader), and new ones (see Publication III). Moreover, focusing specifically on the social-related challenges of NDPs, this research builds upon the research by (Whitton 2011; Bond et al. 2004), increasing the existing knowledge by identifying social-related challenges of NDPs and their consequences, as well as developing some guidelines on how to tackle these challenges (Publication II).

Lastly, seizing the opportunities that emerged during the development of this research, two NDP characteristics that emerged as relevant for the NDP performance during the research development have also been investigated in detail. These consists of the communication about scope changes (Publication V) and the application of VM in the nuclear decommissioning industry (Publication VI). Publication V contributed mostly to the literature on information management (Bevilacqua et al. 2015; Hicks 2007), by proposing a methodology to investigate inefficiencies and applying it to the real case of a project-based company. Publication VI mainly contributes to the literature on value management (Lin et al. 2011; Shen & Liu 2003), by highlighting the requirements for the implementation of VM in decommissioning. The publications in Section B provide more details about their specific contributions to the literature, as summarized above. So, for example, Publication II contributes to the literature on stakeholders' management, while Publication VI contributes to the literature on VM.

C.2.3 Managerial implications

Specifically referring to the nuclear decommissioning context, the research presented in this thesis offers support for project managers by not only equipping them with a methodology to investigate the NDP characteristics that affect the NDP performance (Publication I), but also by illustrating the findings from the direct application of this methodology on NDPs (Publications II, III and IV). Moreover, this research performs an in-depth investigation of two NDP characteristics, i.e. the communication about scope changes (Publication V) and the role that VM can play in decommissioning (Publications VI), whose findings can support project managers in the delivery of future NDPs with improved performance.

In particular, concerning social-related challenges, this research offers guidance on stakeholders' management, both by highlighting "macro" social-related challenges that affected NDPs investigated at site-level (cross-comparing NDPs as in Publication II), but also by highlighting social-related challenges that affect the delivery of a major projects within the UK nuclear decommissioning industry at a "micro" level (see Publication V). Indeed, findings from Publication II highlight how personnel transition and public unacceptance cause respectively underestimated personnel costs and the abandonment of the NDP. Moreover, it proposes guidelines to address these social-related challenge. Conversely, Publication V highlights how the mapping and visualization of the process to communicate scope changes can be the starting point to develop formal and informal amendment in order to reduce stakeholders' frustration, optimize the communication flow and ultimately improve the project performance. Additionally, Publication VI provides advice for project managers on how to apply VM on the case of NDPs, ultimately supporting the delivery of NDPs with improved performance. From these findings, managers in the nuclear decommissioning industry are urged to focus not only on the strictly technical aspect of decommissioning, but also to re-think the importance of social-related challenges, as well as ways to address them.

Furthermore, findings from Publication III equip project managers with a list of NDP characteristics that affect the NDP performance, according to senior practitioners of European NDPs. This is of interest both for project managers entering the nuclear decommissioning industry, but also for more senior project managers already in the industry. In fact, the findings from this research provide an overarching perspective on the NDP characteristics that affect the NDP cost and time performance, which project managers can use to increase their understanding of the European nuclear decommissioning industry.

Moreover, and specifically referring to the NDP cost performance, Publication IV provides valuable insight on statistical tests suitable for the analysis of small sample sizes, in order to highlight the relationship between the project characteristics and their performance, as well as exemplifying the application of the selected statistical tests on 24 NDPs where cost information is publicly available. This equips project managers with a statistically-based approach that could support their decision-making process.

In summary, this PhD research contributes to a better understanding of the project management challenges of NDPs and increases the project managers' awareness regarding the NDP characteristics that affect the NDP performance. The next sections summarize the achievement of the research aim and objectives.

C.3 Achievement of the research aim and objectives

This research has achieved its research aim by addressing each of the research objectives introduced in section A.2. Each of these research objectives was achieved by firstly understanding the limitations of every single piece of research, by detailing the research design, and by presenting the results in the form of a journal publication (see section B).

Concerning the "primary objectives":

- Objective I has been achieved, and the developed methodology based on benchmarking suitable to investigate NDPs is described in Publication I;
- Objectives II, III and IV have been achieved through the research presented in Publications II, III and IV.

Concerning the "secondary objective", i.e. the selection of two NDP characteristics to investigate in details:

- Objective V.a has been achieved through the research described in Publication V, focusing on the communication about scope changes;
- Objective V.b has been achieved through the research described in Publication VI, on the application of VM in the nuclear decommissioning industry.

The next sections provide a summary explanation of the research findings per each piece of research.

C.3.1 Objective I

Objective I: to develop a methodology based on benchmarking to improve learning across projects and investigate the project characteristics that affect the project performance.

The research presented in Publication I describes the methodology based on benchmarking developed to investigate the project characteristics that affect the project performance. This methodology is based on benchmarking, and it suggests to perform both qualitative and quantitative (e.g., respectively, cross-comparison of projects and the application statistics), in order to identify best practices and generate ideas for improvement, in this way promoting the learning across projects. This methodology was developed considering the context of megaprojects and its application is exemplified in the case of NDPs. However, this methodology can be tailored to other projects in other industrial sectors.

From its first conception, the methodology based on benchmarking developed to achieve the first research objective has iteratively evolved into the one presented in Publication I. Moreover, during its application, the author further tailored it, in order to address the challenges of each specific piece of research. For example, the Publication I contains only limited details, about how to cross-compare NDPs and suggests only the Fisher's exact test but not the Barnard's test. These "additional details" added when applying the research methodology (and described in Publication II, III and IV) have not been mentioned in Publication I as they depend on the specific context of each piece of research and its limitations, while Publication I aimed to reach a broader audience (e.g. researchers investigating mega construction projects, who for example might be able to access to a larger number of potential interviewees and might, therefore, decide to send a written survey questionnaire). The fact that Publication I does not include these "details", does not denote incompleteness in the description of the methodology presented in Publication I. Conversely, this simply underlines that fact that during the actual application of this methodology, the researcher still plays an essential role in understanding the research context. This tailoring is subject, for example, to new information becoming available in time (such as, concerning this research, relevant publications such as (OECD/NEA 2016; European Court of Auditors 2016) and the code in R to perform the Barnard's test. Hence, it can be concluded that objective I have been achieved.

C.3.2 Objective II

Objective II: to investigate social-related challenges of NDPs as site-level endeavours.

Research questions [Objective II]:

- *Which are the main social challenges that arise during the development of a NDP, and how do they affect NDPs?*
- *Which are the best practices to socially and ethically manage these challenges, and successfully meet the scope of the project?*

The research presented in Publication II addresses the abovementioned research questions and highlights the main social-related challenges that arise during the development of a NDP, i.e. personnel transition and public unacceptance, which lead respectively to the underestimation of personnel costs and the abandonment of the NDP. Moreover, this research provides high-level guidelines on how to address these social challenges, i.e. by engaging early and timely the local community, starting the planning of the NDP as soon as possible and possibly when the facility is still operating, and privileging the siting of a waste storage/repository where a nuclear licence has already been granted. In doing this, the paper also suggests to firstly consider the stakeholders logistically closer to the nuclear facility and cluster them into groups (e.g. direct employees, suppliers, etc.) and timely engage them by involving them into institutionalised dialogue, in order to avoid surprises regarding NDP and to manage the decrease of the staff needed during decommissioning also according to the individual needs and preferences. Therefore, it can be concluded that the research presented in Publication II achieve objective II.

C.3.3 Objective III

Objective III: collect and analyse the characteristics of NDPs that affect the NDP cost and time performance.

Research questions [Objective III]:

- *Which NDP characteristics affect the difference between time and cost estimates of NDPs and the NDPs' actual time and costs?*

The research illustrated in Publication III collects and analyse the NDP characteristics that affect the NDP time and cost performance, by applying content analysis on the information collected by interviewing experienced NDP practitioners. The NDP characteristics include the uncertainties and unknowns about the site condition and the consequent need for additional characterization, the limited clarity of the waste routes and availability of storage and disposal facilities, as well as the clarity of scope and site end-state

C.3.4 Objective IV

Objective IV: to present a systematic approach to test the association between the NDP characteristics and the NDP performance through statistics.

Research question [Objective IV]:

- *How can the relationship between NDP characteristics and NDP performance be assessed through statistics?*

The research in Publication IV achieves objective IV by selecting and applying with an illustrative purpose two statistical tests, in order to explore the association between the operationalizable NDP characteristics that affect the NDP cost performance. As explained in section A.3, Publication IV focuses on the NDP cost performance, due to the virtual absence of information about the duration of NDPs and its change over time.

Publication IV highlights the NDP characteristics that present an association with the NDP cost performance highlighted by a p-value of either the Fisher's exact test or the Barnard's test or both lower than 10%. These findings, however, have to be taken in a circumspect way due to the low quality of the input data in terms of the NDP cost performance. Also, it is important to underline that the absence of an association does not mean that the corresponding NDP characteristic is not relevant, but simply that this association does not emerge from the implementation of the statistical tests on the specific sample of European NDPs that have been selected. This stresses the importance of the researcher's role and her knowledge of the single NDPs, especially during the tentative explanation of the actual relevance of the NDP characteristics that emerge from the implementation of the two selected statistical tests.

C.3.5 Objective V.a

Objective V.a: to analyse the communication about scope changes in nuclear decommissioning, showing the importance of monitoring and addressing 'weak signals' (e.g. frustration)

Research questions [Objective V.a]:

- *To what extent should and could weak signals of stakeholders' discomfort be used to highlight operational inefficiencies on the information flow associated with high transaction costs?*
- *How can communication and information management be improved to address the stakeholders' discomfort, optimise the information flow and ultimately increase the overall project performance?*

The research presented in Publication IV deals with objective V.a, and addresses the research questions above by developing a five-steps framework and applying it to the case of a large project-based company engaged in the engineering and manufacturing of complex piece of equipment costing millions of pounds, for its strategic long-term client, both in the field of nuclear decommissioning. The five steps consisted of (1) the understanding of the context, (2) the data collection and validation, (3) the creation of the current-state, (4) the analysis of the current-state and (5) the development of improvement objectives, i.e. suggestions for project managers about both formal and informal changes that could improve the communication flow.

The first three steps enable the authors to address the first research question and allow the visual representation of the company current-state, as well as the "frustration points" which are argued to be indicators of operational inefficiencies and therefore potential ways to lower transaction costs. Instead, the last two steps address the second research question by suggesting how to improve the communication flow about scope changes and consequently reduce the stakeholders' discomfort. Overall, this allowed to analyse the communication about scope changes in nuclear decommissioning, showing the importance of monitoring and addressing 'weak signals' (e.g. frustration), i.e. to reach objective V.

C.3.6 Objective V.b

Objective V.b: to explore the potential role of VM in nuclear decommissioning.

Research question [Objective 6]:

- *What does "value" mean in the context of decommissioning?*
- *What are the constraints that affect decommissioning projects that can be addressed with VM?*
- *What are the requirements for a successful implementation of VM in decommissioning projects?*

Publication VI illustrates the research performed to answer these research questions, addressing in this way objective V.b. More specifically, Publication VI introduces the topic of decommissioning to the literature on VM, traditionally focused on construction projects. Moreover, Publication VI promotes the discussion of what "value" means in decommissioning, it collects and analyses information about which of the constraints of decommissioning projects can be tackled through VM, and presents the requirements for successful VM in decommissioning.

C.4 Limitations and future research

This exploratory research is affected by a number of limitations that the author suggests addressing in future research. First of all, this research was limited by the sample size, the availability of information and the limited project management academic research in these industrial sectors. For these reasons, the author focused on cost and time performance of NDP performance, and suggests future research on other NDPs performance (e.g. in terms of environmental performance), but also from different perspectives and at a distance of months and years from the end of the completion of the NDP.

A second limitation of this research is the decision to focus on European NDPs. Hence, future research could investigate other geographical contexts, such as US NDPs. Indeed, both the investigation of US NDPs and their comparison with European ones could provide interesting findings. Nevertheless, any cross-comparison will need to take into account the considerable differences between US and European NDPs, for example in terms of the regulatory environment, the size of the licensed site and the free space available within the geographical perimeter of the NDP to progress with decommissioning.

Additionally, every single publication triggers thoughts for future work. For example:

- ➢ The methodology of Publication I (in this research applied on NDPs), could be re-applied to other industrial sectors and industrial context, and findings (when suitable) could be compared with the ones on NDPs;
- ➢ Publication II triggers further in-depth investigation of how to engage both internal and external stakeholders;
- ➢ Of the list of NDP characteristics that emerge from the research presented in Publication III, every single one could be scrutinized in more details;
- ➢ The statistical tests suitable for small sample sizes, selected and applied on NDPs in Publication IV, call for future application in other industrial sectors. Moreover, other analysis (such as Qualitative Comparative Analysis (QCA)) could be applied to investigate how the different project characteristics combined affect the project performance. Additionally, further research probing causations could be pursued;

- Publications V suggests more investigation of the topic of scope changes, for example investigating how different contractual approaches deal with changes.
- Publication VI triggers the discussion on “what is the ultimate value” of a NDP, a discussion that could be expanded to non-nuclear decommissioning projects as well..

More details on possible future research are emphasized in each of the publications in section B.

C.5 Concluding remarks

Decommissioning projects are a new and growing challenge that project managers need to deal with in the very near future. Among other decommissioning projects, NDPs are the most complex, long and expensive, and there is only limited understanding of how to improve their performance. However, their fast growing number increases the urgency to investigate what affects their performance. Nevertheless, there is still extremely limited project management research on NDPs. This research is a first step to bridge this gap in knowledge. More specifically, this research develops and applies a methodology based on benchmarking to investigate the NDP characteristics that affect the NDP performance.

Key findings of this research include the fact that personnel transition from operations to decommissioning and public unacceptance are two social-related NDP challenges that hinder the progress of NDPs. Moreover, from this research, it emerged that there are a number of other NDPs characteristcs that affect the NDP time and cost performance. These include the uncertainties and unknowns about the site condition and the consequent need for additional characterization, the limited clarity of the waste routes and availability of storage and disposal facilities, as well as the clarity of scope and site end-state. In this research, the relationship between the operationalizable NDP characteristics and the NDP cost performance has also been tested through statistics. Finally, two NDP characteristics have been investigated in more detail.

This research lays the path for considerable future research, both investigating each of the NDP characteristics that have emerged, as well as investigating their interconnectedness.

D. Appendix

D.1 Publications [a] and [b]

Publication [a]

Invernizzi, D.C., Locatelli, G., Brookes, N.J. and Grey, M. (2017), “Similar but different: a top-down benchmarking approach to investigate nuclear decommissioning projects”, paper prepared and presented in the International Conference on Nuclear Engineering, ICONE25, July 2017, Shanghai.

Publication [b]

Invernizzi, D.C., Locatelli, G., Brookes, N.J., (2017), “Cost overruns –helping to define what it really means” – published in the Proceedings of the Institution of Civil Engineering (ICE).

Publication [a]

“Similar but different: a top-down benchmarking approach to investigate nuclear decommissioning projects”

Proceedings of the 2017 25th International Conference on Nuclear Engineering
ICONE25
May 14-18, 2017, Shanghai, China

ICONE2566155

SIMILAR BUT DIFFERENT: A TOP-DOWN BENCHMARKING APPROACH TO INVESTIGATE NUCLEAR DECOMMISSIONING PROJECTS

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ABSTRACT

Project management literature has, until now, mainly focused on new build and only in the last decades the issues of decommissioning (mega) projects has arisen. To respond to this changing environment, project management will need to understand the challenges of decommissioning projects. Decommissioning projects within Oil & Gas, Chemical and Nuclear sectors are characterized by high costs, long schedules and uncertainty-based risks. The budget for Nuclear Decommissioning Projects and Programmes (NDPs) are subject to well publicized increases and, due to their relatively recent emergence, complexity and variety, key stakeholders lack a full understanding of the key factors influencing these increases.

Benchmarking involves "comparing actual or planned practices […] to identify best practices, generate ideas for improvement" [1] and offers significant potential to improve the performance of project selection, planning and delivery. However, even if benchmarking is the envisaged methodology to investigate the NDPs characteristics that impact on the NDPs performance, until now, it has only been partially used and there is a huge gap in the literature concerning benchmarking NDPs.

This paper adapts a top-down benchmarking approach to highlight the NDPs characteristics that mostly impact on the NDPs performance. This is exemplified by a systematic quantitative and qualitative cross-comparison of two major "similar-but-different" NDPs: Rocky Flats (US) and Sellafield (UK). Main results concern the understanding of the alternatives of the owner and/or the contractors in relation to (1) the physical characteristics and the end state of the nuclear site, (2) the governance, funding & contracting schemes, and (3) the stakeholders' engagement.

1. INTRODUCTION

Knowledge in managing construction (mega) projects has been built throughout the centuries, starting from the Babylonian & Assyrian temples (nine thousand years ago) and the Egyptian Pyramids (four thousand years ago). Since then, this knowledge has been vastly improved by practitioners and, in the last decades, it has also been broadly scrutinized by academics. In fact, the vast majority of the project management literature focuses on new build, with countless research on "success factors" and "success criteria" [2–4]. Conversely, only limited attention has been paid to the end-of-life of infrastructure and their decommissioning. This is partially due to the fact that the number of the completed decommissioning projects is negligible compared to the new build. For instance, in the nuclear industry, more than 500 NPPs have been built throughout the 20th century (and still the construction of new units is an enormous challenge), while only 16 NPPs have been fully decommissioned [5], so the reader can understand the gap and the relevance of further researches in this field.

Nuclear decommissioning is a long, expensive and complex process with a multidisciplinary nature [6]. It's 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*" [7]. The World Nuclear Association [8] 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 [9] strictly defines the start of nuclear decommissioning "*after the nuclear fuel, coolant and radioactive waste are removed*". The IAEA

[7] focuses on the end of decommissioning and points out that it "*typically includes dismantling of the facility […] but this need not be the case*". In the UK, the Office of Nuclear Regulation [10] provides advice on when to consider operations to cease and decommissioning to start, and waste management is considered to be an integral part of decommissioning and dismantling, as (in terms of the process) they cannot be separated, and costs need to be appraised together. NDPs are long and expensive, but are also characterized by extreme variety of designs and legislation, which (in part) creates strong uncertainties that hinders the reliability of schedule and costs estimates. Therefore, the costs estimates for these projects keep increasing and key stakeholders lack a full understanding of the key determinants that engender these phenomena [11–14].

Despite this extremely high relevance, there is a huge gap in the literature concerning benchmarking NDPs. This research helps to fill this gap and adapts benchmarking to the challenges of the nuclear decommissioning industry. The cross-comparison at a site-level of two selected NDPs exemplifies this methodology to investigate the NDPs characteristics that impact on the NDPs performance. This research collects a list of NDPs characteristics and criteria to evaluate the NDPs performance and statistically assess the correlation and causation between them. The qualitative and quantitative cross-comparison based on benchmarking explained here lays the foundation to the subsequent statistical analysis, which will enable the drafting of empirically-based guidelines to establish sustainable improvement objectives and support the selection, planning and delivery of future NDPs.

The paper is organised as follows: section 2 reviews the project management literature on "success factors" and "success criteria", highlighting the limited consideration posed on nuclear decommissioning; section 3 presents the methodology to quantitatively and qualitatively benchmark NDPs and exemplifies this methodology through a systematic cross-comparison of two NDPs: Rocky Flats (US) and Sellafield (UK); section 4 and Table 1 in the Appendix highlight the results in relation to the alternatives of the owner and/or the contractors in relation to (1) the physical characteristics and the end state of the nuclear site, (2) the governance, funding & contracting schemes, and (3) the stakeholders' engagement. Lastly, this paper presents a deep reflection on the benefit and the way forward for the application of benchmarking in the nuclear decommissioning industry.

2. LITERATURE REVIEW

2.1. "Success factors" and "success criteria"

In the last decades, project management literature has vastly investigated the "success factors" that impact on the success of the projects, measured through the so-called "success criteria". Project "success criteria" are defined as the measures by which the successful outcome of a project is assessed, while "success factors" are the elements of a project that can be influenced to increase the likelihood of success [15]. The search of these key words in Scopus (as in October 2016) restricted to the field of "project management" highlights more than a hundred publications in the last 5 years, with great emphasis posed on "success factors" and "success criteria" in the construction industry. Traditional "success criteria" in project management refers to the so-called iron triangle, i.e. cost, time and quality, however this short-term, contract-based view has been overtaken by researches that analyse multiple perspectives of different stakeholders in different timeframes [16–18]. For instance, a common "success criteria" is respecting the budget, while "success factors" can be a detailed Front-End-Engineering-and-Design (FEED) or the early engagement of external and internal stakeholders [19–21].

Recently, Williams [22] has emphasized that it is increasingly recognized that the nature of project success is "*multidimensional, with different criteria, only some clearly measurable*" and states that there is still limited understanding in the "*causal chains through which success emerges*". Zavadskas et al. [23] also analyse common construction performance, focusing on what they call project management "problems" against the "success factors", illustrating how to assess the projects' efficiency using aggregated indicators. Gunathilaka et al. [24] review conceptual and empirical research papers, the relationship between project success factors and project success criteria, focusing on construction management journals, and highlight the scarce empirical evidence that support the actual correlation between them. Bassam [25] does not limit his research to the construction filed, and employs statistical analysis to examine the correlations between the risk factors that are common to success criteria, to conclude that there are some factors in the initiation phase that could lead to the occurrence of additional risk factors in the implementation and evaluation phases. Stemming from the aforementioned researches, this paper draws the attention on the importance of analysing the characteristics that impact on the performance of NDPs. In fact, even if some authors investigated the long-term projects performance (such as Fahri et al. [26], who go beyond the project close-out stage and Zavadskas et al. [23], who illustrates the importance of assessing performance "*not only at the end of project but also during all project life cycle*"), the project management researches on NDPs are still scarce.

This is also proved by the fact that the search of "success factors" and "success criteria" limited to the field of "nuclear decommissioning" (exact query: "success factors" AND "success criteria" AND "nuclear decommissioning"), produces zero results in Scopus (as in October 2016). Therefore, the authors argue that there is a need to expand this area of research.

2.2. NDPs characteristics and NDPs performance

The investigation of NDPs characteristics that impact on the NDPs performance is limited and has attracted the attention of researches only in very recent years. Studsvik et al. [27] focus on the importance of experience-based decommissioning planning and examine the importance of waste management aspects, summarizing the importance of:

- identify and mitigate bottlenecks and showstoppers (e.g. undersized materials),
- avoid sub-optimization (e.g. compatibility of different steps),
- minimize wastes amount for disposal (e.g. limited understanding of the radiological status).

Sykora et al. [28] highlight the overall importance of early preparation for decommissioning and describes AREVA's experience both on research and power reactors and recommend to:

- build a decommissioning team composed by both plant staff and D&D specialists,
- insist of pre-work and radiological characterization,
- develop a tailored decommissioning manual,
- replace the plant's legacy support systems with modular and lighter systems fit for D&D purposes that allow to accelerate D&D activities.

Locatelli & Mancini [12] perform a systematic cross-comparison and summarize two potential emergent groups of explanations for the poor performances of these projects, i.e. (1) FOAK issues in terms of both the capabilities of the architect-engineer and the supply chain and (2) poor forecasting leading to unrealistic targets. These aspects affect not only the new build but also the selection, planning and delivery of decommissioning projects. Locatelli & Mancini [29] also investigate the comparison between large and small scale reactor decommissioning, focusing on their differential cost drivers. In their analysis, the authors compare among cost drivers for the decommissioning cost of small reactors vs large ones, and highlight differential cost drivers, e.g. size of reactor, number of units on the site, amount of waste, technological changes, decommissioning strategy options, operating history, type of reactor, site reuse, scope of decommissioning activities, clearance and classification level, regulatory standard, availability of radioactive waste repositories, uncertainties and uncertainty of treatment, labour cost and social and political factors.

The IAEA [30] focuses on small research reactors and other small facilities highlighting the specific factors to be taken into account, i.e.:

- the scale, since e.g. (1) economies of scale will be limited, which may raise the costs compared to bigger facilities, (2) there will be less flexibility, so a delay in one area is more likely to impact on the whole project schedule, (3) there might be space limitation that restrict work;
- the radiological hazard, as (1) relatively small source terms should lead to relatively small hazards, risks and waste streams, but (2) there may be a wider range of nuclides than in large facilities, depending on the work previously undertaken at the facility;
- the resource limitations, due to e.g. (1) regulations that may be inadequate, (2) the reduced size of the project may cause a lack of attractiveness in the development of specific technology, (3) records of the facility that have not been transferred properly, (4) the investment needed for infrastructure that may seem prohibitive;
- the lack of comparable facilities, since there may be many research reactors in operations but extrapolations from one to another may be complex;
- Site-specific costs estimates, due to the "one-off nature of some facilities", the managerial and administrative burden, etc.

Moreover, similarly to construction projects, the cost performance of NDPs have raised particular interests of researchers. Kim & Mcgrath (2013) focus on the cost performance of eight NPPs, highlighting the factors that have the biggest impact on their performance, concluding that for five of these plants, (1) staffing costs were in the range 29-52% of the total decommissioning costs, (2) removal costs ranged between 19-26% of total decommissioning costs, (3) radioactive waste management are highly dependent on the strategy implemented and waste disposal costs ranges from 17 to 27%.

Also the OECD/NEA [32] focuses of the costs and classifies key costs elements into "very significant" and "moderately significant". "Very significant" cost elements are:

- Scope changes and scope growth of the project;
- Regulatory changes and increased requirements for additional information and detail;
- Stakeholders impact on end-point state and disposition of wastes;
- Site characterisation of physical, radiological, and hazardous materials inventory;
- Waste storage and the availability of ultimate disposition facilities;
- Disposition of spent nuclear fuel and on-site storage prior to a permanent repository;
- Clean structure disposition;
- Contingency application and use in estimates to account for unforeseeable events;
- Knowledge management of experienced personnel;
- Standardisation of the cost report format to ensure all cost elements are included;
- Assumed duration of the dismantling and clean-up activities.

Lastly, even if benchmarking provides a basis for measuring performance and is the envisaged methodology to compare actual practices to identify best ones and generate ideas for improvement [1], it remains remarkably under-investigated in the nuclear decommissioning sector.

By drawing on the aforementioned concepts, the authors present an empirically based cross-comparison of two NDPs based on a top-down approach. The top-down approach is a way to break-down a system (big picture) and gain a better understanding of its sub-systems (detailed components). 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 and derive direct labour, equipment and overhead costs [33]. The aim of the top-down approach is not to produce cost estimates, but to present different scenarios and the NDPs characteristics that have the biggest impact on the performance.

3. METHODOLOGY

3.1. The need to adapt benchmarking to NDPs

In the 1990s, Büyüközkan & Maire [34] stated that benchmarking was one of the most efficient and effective management tools to help an enterprise to improve its performance and that it was a cyclical, “never-ending and learning” process. However, when Longbottom [35] investigated the status of benchmarking (focusing on the UK), he realised that benchmarking was not so well-established as a common practice as suggested by the literature. Within the construction industry, for instance, the interests in benchmarking has risen because finding examples of superior performance firms can adjust their policies and practices to improve their own performance [36–39].

Nevertheless, the benchmarking analyses performed by these authors cannot be directly applied to the nuclear decommissioning industry, mainly due to the unfeasibility of collecting dozens of projects (as in [36,37]) and the challenges that the nuclear decommissioning industry shares with the construction one, such as the alleged “uniqueness” of projects and the intense effort required to establish and incorporate a project performance measurement system [37], and the difficulty of obtaining data, the insufficient resources and overall internal resistance [39]. Indeed, even if benchmarking can be summarized into three main phases, i.e. (1) plan (develop a project proposal), (2) perform (recruit and work with participants, collect and compare data) and (3) improve (improve the organization) [40], or described through the 13 common steps by [41], benchmarking still needs to be adapted case-by-case to the specific project under scrutiny. This can be particularly challenging for the nuclear decommissioning industry, and only few publications mention “benchmarking” explicitly. One of these is by the OECD/NEA [42], which supports the benchmarking analysis, stating that “it can been a valuable exercise”, especially when costs and schedule estimates are compared to actual performance, and can be accomplished through a comparison of (1) decommissioning costing formulae, (2) other studies, (3) actual field experiences.

The OECD/NEA [33] proposes the International Structure for Decommissioning Costing (ISDC) of nuclear installations, which will be helpful for international bottom-up cost-comparison. Before the ISCD, an example of comparison of decommissioning formulae and costs estimates was published by Bewon & Jonsson [43], who presented a comparative analysis of two Swedish NDPs, i.e. the Oskarshamn 3 and Barsebäck, explaining the importance of selecting two cases that share some characteristics in terms of project environment.

Conversely, the study performed by the Öko-Institut [44] does not limit the focus on the cost assessment and presents an empirically-based organizational comparison among 6 different countries, namely France, Germany, the UK, Bulgaria, Lithuania and Slovakia. Conclusions list several recommendations regarding the need to improve national control conditions, the responsibility of the managing organisation, and the attribution of clear responsibilities.

Similarly to [44], this paper collects, selects and compares two NDPs This cross-comparison paves the way for developing the methodology presented in Figure 1 to ultimately investigate the statistical correlation and causation between NDPs characteristics and NDPs performance.

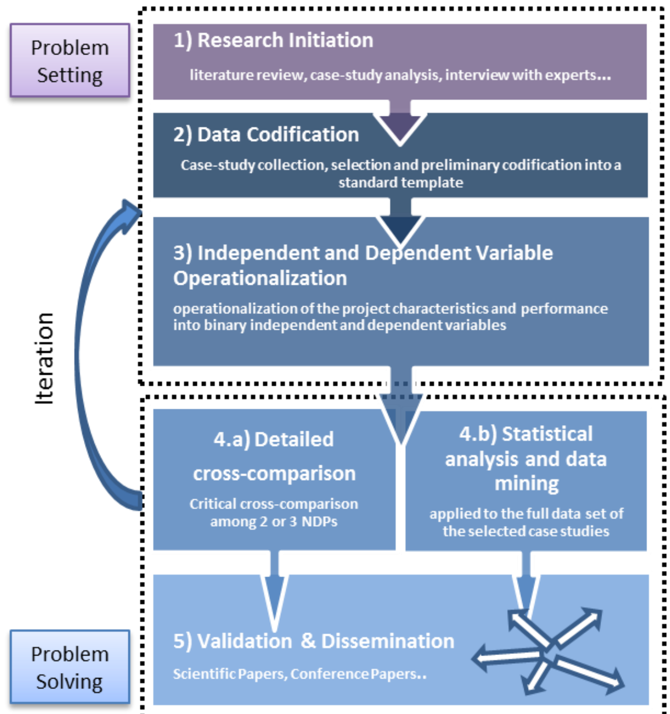

Figure 1. The research framework

3.2. Collection and Selection of NDPs

The literature investigating NDPs characteristics that are correlated with the NDPs performance is still limited (at least partially) because of the low number of nuclear facilities that have been completely decommissioned. This is due to the following main reasons:

- Early nuclear facilities were designed for a life of 30 years [8], 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 [45];
- Newer nuclear facilities have been designed for a life of 40 – 60 years [8], so, for instance, the NPPs installed have not reached the end of their forecasted lifecycle yet;
- Some nuclear facilities have benefited (or will benefit) from a lengthening of their operating licence [46].

Rocky Flats (US) and Sellafield (UK) have been selected for this analysis because of the availability and of public information in English and because they:

- are recent NDPs;
- 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);
- have a comparable size;
- had a decommissioning budget in the order of dozens of billions of $.

As explained thoroughly in the Appendix, Rocky Flats is an example of NDP completed under budget, and therefore the differences highlighted by the cross-comparison with Sellafield can produce relevant lessons learned. The two NDPs are described through their characteristics, summarized into three macro-categories, i.e.:

- Overview of the NDP, physical characteristics & end state;
- Governance, funding &contracting scheme;
- Stakeholders and stakeholders' engagement.

The cross-comparison of Rocky Flats (US) vs Sellafield (UK) is presented in the Appendix in Table 1 and Figure 3.

4. CONCLUSION

The cross-comparison between Rocky Flats (US) and Sellafield (UK) presented in the Appendix both supports the findings of the literature of Section 2.2 and complements it with new NDPs characteristics that contributed to the successful performance of NDPs (see Table 1). Indeed, even if these two NDPs are remarkably different, early results from their cross-comparison highlight the importance of several NDPs characteristics, e.g.:

- The physical characteristics of the site, such as the size of the free space available within the perimeter of the nuclear site to manage radioactive material, i.e. the presence of a "buffer zone";
- Funding arrangements and contracting schemes, e.g. the allocation of incentives, the sharing of risks with the government, etc.);
- Early and timely engagement with external and internal stakeholders.

The cross-comparison of Rocky Flats and Sellafield also highlighted the pivotal role of radioactive waste management: Rocky Flats was not an operating facility anymore and its waste was shipped to other states in the US, while Sellafield still handles radioactive material that is shipped both from other UK nuclear sites (within the UK) and other countries as shown in Figure 2.

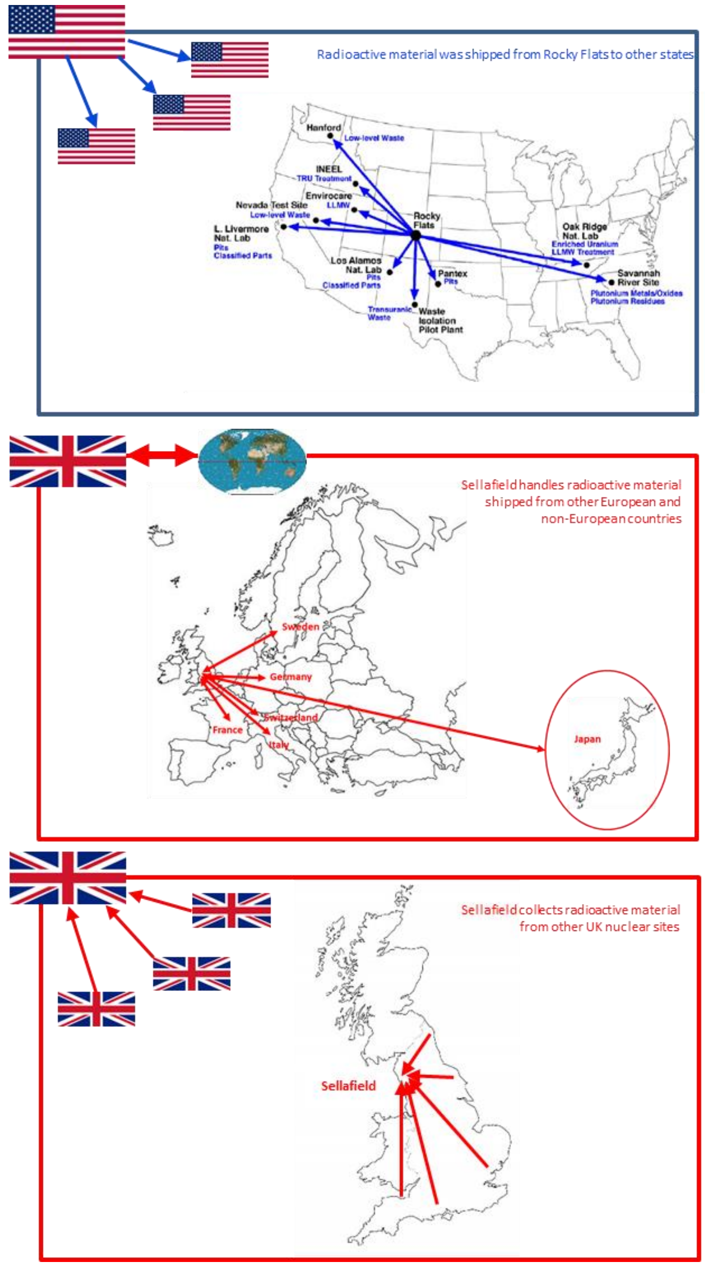

Figure 2. Radioactive waste management in Rocky Flats vs Sellafield, adapted from [47,48]

NOMENCLATURE

D&D = Decommissioning and Dismantling; FEED = Front-End-Engineering-and-Design; FOAK = First Of A Kind

ISDC = International Structure for Decommissioning Costing; NDPs = Nuclear Decommissioning Projects and Programmes

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authors, and the authors are the only responsible for any omission or mistake. This paper does not represent in any way the point of view of NNL or NDA or any other organization involved in the decommissioning process of nuclear facilities either in the UK or abroad.

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ANNEX A

CROSS-COMPARISON OF NDPS: ROCKY FLATS (US) VS SELLAFIELD (UK)

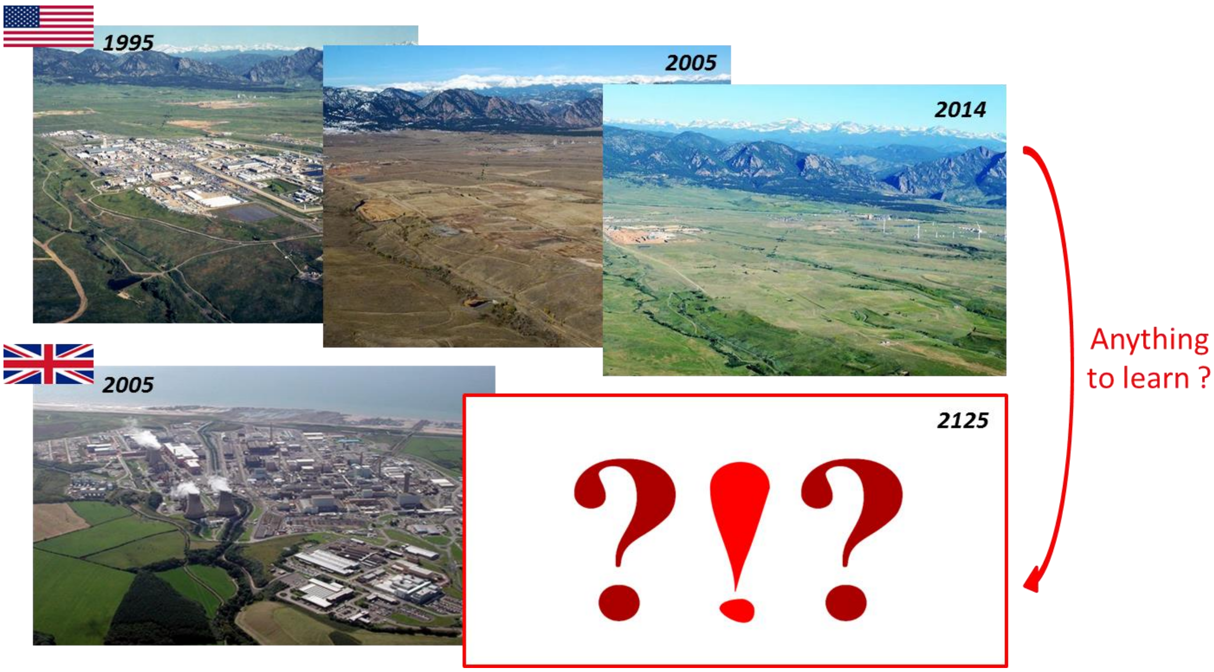

Figure 3. Rocky Flats NDP vs Sellafield NDP

Rocky Flats vs Sellafield	**Rocky Flats[1] (US)**	**Sellafield[2] (UK)**	**Cross-comparison and comments**
Overview of the NDP, physical characteristics & end state	-Rocky Flats was a nuclear weapons production facility that **produced plutonium and enriched uranium** from 1953 until 1989. It was owned by the Department of Energy (DOE) and was managed by a series of weapons contractors. -Rocky Flats consisted of **1.56 km^2** of production area, and **24.3 km^2** of open area referred to as a "**buffer zone**". The site hosted 800 building within the perimeter of the nuclear site, with approximately **0.3 km^2** underroof -Rocky Flats final end state **is brownfield**, with no buildings remaining on site, but restriction regarding the usage of land. -Few **accidents** occurred in Rocky Flats during its operations, e.g. the largest industrial fire in the nation's industry incurred in 1969. This provoked a demonstration that involved 10,000 people. This accident followed two previous ones in the 50s and 60s. -In 1989, the FBI raided the Rocky Flats because of suspicion that unreported pollution might be occurring. From 1989 to 1992, the workforce doubled in size to produce documents verifying production level. In 1992 the Rocky Flats nuclear program was permanently withdrawn. -In 1995 the DOE estimated that the clean-up and the closure of the facility would require more than **70 year and $ 36 billion**. In the same year, a joint venture won the contract demonstrating that they could close the project **by 2006 for $ 3.963 billion. In October 2005,** 800 buildings had been demolished, all radioactive waste had been removed and soil and water had been remediated, with a final cost of less than **£ 3.5 billion, in 5 years**, i.e. 14 months in advance on the 2000 estimates [49]. Moreover the remediation pollution levels surpassed initial federal standards [50].	-Sellafield site was a Royal Ordnance Factory and **produced explosives** for the war effort in the early 1940s [51], and its history is described by [52]. -Sellafield hosts around 1,400 buildings, of which 240 are nuclear (operating [53]) facilities, concentrated in 6 km^2 site [54]. -The worst nuclear **accident** in UK history, ranked in severity at level 5/7-point on the International Nuclear Event Scale occurred in Sellafield, in 1957: the Windscale fire burned for three days. -Sellafield currently includes two operational nuclear fuel reprocessing plants, a waste treatment and storage plants, legacy storage ponds and silos for nuclear waste material [53] and it is owned by the Nuclear Decommissioning Authority [48]. Sellafield is not only reprocessing UK fuel, but also fuel from e.g. Japan [52]. -Sellafield decommissioning estimates keep increasing and currently reach **more than £ 53 billion and more than 100 years** [55]. -Sellafield final end state will be **brownfield**, with storage/repository facilities eventually remaining on site.	-Both facilities were born with **military purpose.** -Sellafield was subsequently chosen for the UK first nuclear reactors due to its comparative remoteness, coastal position, existing infrastructure and access to water supply [51]. -The size of the two sites is comparable. Rocky Flats, however, had a **buffer zone** which surrounded the site. This is helpful for the management of radioactive material. Sellafield, on the contrary is "packed with buildings" (informal talks with Sellafield employees) -Both NDPs consists of **a group of facilities**. -Both facilities have experienced **major nuclear accidents.** -Sellafield site hosts facilities that are still operating while decommissioning takes place. Sellafield also **collects waste from other nuclear sites of the same country & from other countries,** while Rocky Flats NDPs shipped to other material disposition sites [47]. -Both NDPs are **First-Of-A-Kind**, since no-one performed something similar to Rocky Flats before [50] and Sellafield host the "most diverse portfolio of any nuclear site in the world" [54].

[1] Main Ref [49,50,60].
[2] Main Ref [58,61]

Governance, funding & contracting scheme	Few factors in the governance, funding and contracting scheme promoted the Rocky Flats NDPs, e.g.: -Rocky Flats adopted the so-called "**abundance approach**", where the aim is to fill the gap between forecasted successful performance and "spectacular" performance, i.e. to achieve positive deviance by closing the abundance gap [50] -The contract was an **incentive-based** project management contract in which employees could only get paid for accomplishing real things [50,56]. -**Incentives were also singularly allocated to employees** who promote feasible ideas to improve the performance of the decommissioning project and contract specifications. -The "**learn-as-you-go**" strategy was adopted and progress were **performance-driven**. -In the 1995 contract, **the government was sharing the responsibility** and the concept called "**government - furnished equipment and services**," or GFS&I was adopted. -From the DOE perspective, there was a single-point performance expectation, i.e. the 15th December 2006 -the DOE, the EPA, and the state of Colorado signed a **new interagency agreement** called the Rocky Flats clean-up Agreement (RFCA). -Performance were measured bottom-up, and not just top down.	-When the NDA was born, Sellafield Ltd was formally appointed for Sellafield clean-up. On the 1st of April 2016, however, Sellafield Ltd became a wholly owned subsidiary of the NDA [57] -Sellafield approach is closer to what is described by [50] as the "**problem solving approach",** where the aim is to fill the gap between ineffective, inefficient, unprofitable performance and the forecasted performance, i.e. to achieve the expected performance by closing the deficit gap.	-Rocky Flats and Sellafield adopt **different approaches**, respectively the "abundance approach" and the "problem solving approach" -The **incentive-based type of contract** (where the contingent fee that wouldn't be paid until the job was complete), **the government commitment** to timely furnish equipment and services (through the GF&I concept), and the **alignment of objectives** between the DOE, the EPA, and the state of Colorado (stated in the interagency agreement) were all key factors that drove the success of Rocky Flats NDPs. -For Rocky Flats NDPs, directly **sharing the risks with the government** was pivotal to speed the Rocky Flats NDP. -In Rocky Flats NDPs, **measuring performance both top-down and bottom-up** was understood to be a driver for success. Within the NDA, there has been an attempt to measure performance bottom-up, but the initiative was halted by the management (Ref: informal talk with NDA employee)
Stakeholders & Stakeholder Engagement	After the closure of Rocky Flats, there was a need to "**change the culture**" from operations to decommissioning. After 1995, leaders at Rocky Flats initiated **visits** to churches, chambers of commerce, public schools, government agencies, and other interested constituencies to invite participation, express views, and build relationships [50]. Key stakeholders were also: the Federal Government, the DOE personnel, the EPA, the local elected officials, etc. and the **three unions** representing the workers, i.e. steelworkers, construction workers and security guards.	The NDA and Sellafield Ltd engage with both internal stakeholders (e.g. employees, suppliers, etc.) and external stakeholders (e.g. UK Government, regulatory bodies, local community, etc.) timely and continuously, using several different channels, such as the official website [48], [58], public reports, Sellafield-magazines and meetings.	-The importance of **early and timely engagement of stakeholders** (also emphasized in [59]) from the beginning of the accelerated decommissioning project of Rocky Flats proved to be a key factor for its success. -In Sellafield, unlike Rocky Flats, the idea "*100 years to decommissioning it? I will be dead by then!*" remains. In Rocky Flats, a **"change of culture"** was needed to promote the accelerated decommissioning. -This fact also draw the attention on the importance of the forecasted **duration of a decommissioning projects**.

Table 1. Cross-comparison between Rocky Flats NDP and Sellafield NDP

Publication [b]

“Cost overruns - Helping to define what they really mean”

195
Civil Engineering

Cost overruns – helping to define what they really mean
Invernizzi, Locatelli and Brookes

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Cost overruns – helping to define what they really mean

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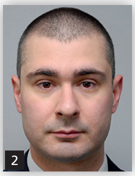
1

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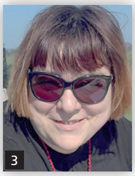
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Civil engineers are often in the firing line for alleged cost overruns, particularly on major publicly funded infrastructure projects. This usually occurs when the final cost of a project is simply compared with the original estimate, even though this was published a long time ago, in different circumstances and for a quite different project to the one carried out. This paper proposes a systematic approach to ensure that cost overruns, should they occur, are more accurately defined in terms of when the initial and end costs are assessed, from which point of view, at which project stage, and including scope changes and financial assumptions. The paper refers to the UK's £163 billion nuclear decommissioning programme.

1. Introduction

Practitioners and academics often discuss construction cost overruns and why they occur. But what is a 'cost overrun'? The answer might seem trivial: a cost overrun refers to the situation where the actual cost is higher than the original estimate. However, in the case of megaprojects, this can be hard to define.

Megaprojects are characterised by a budget of over £1 billion, vast complexity (especially in organisational terms) and a long planning and construction schedule. They are affected by several high-level risks and have a long-lasting impact on the economy, the environment and society (Ansar *et al.*, 2016; Brookes and Locatelli, 2015).

Moreover, especially in the case of large and complex projects, the assessment of the cost overruns is hindered by the issue of data availability, reliability and integrity. Indeed, trying to establish cost overruns is a very difficult task both outside an organisation, due to the lack of publicly available and reliable data, but also within an organisation, because often no proper targets are set.

Consider the example in Figure 1. If a construction project was estimated to cost £100 after the concept screening phase and £150 after the detailed design phase, but the contract was ultimately awarded after the tendering process at £180 and the final actual cost of the project was £178, can it be said with confidence that the project suffered from cost overruns? Or, if the project was approved at concept stage for £200, rose to £230 at the detailed design stage, was tendered for £180 and finally actually cost £230, was this also a cost overrun and if so how much?

This case is comparable to the London 2012 games, where the initial estimates made by the government reached £2·4 billion in 2005 (when London won the bid). These estimates then rose to £9·3 billion, which allowed the Olympic minister to declare that the project was a 'significant achievement' and allowed the government to issue a report on the games being 'under budget', with £476 million of expected savings on the £9·3 billion budget (BBC, 2007; MailOnline, 2012).

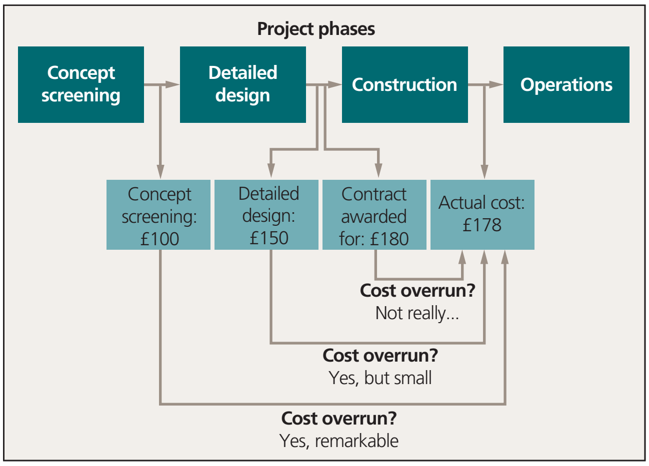

Figure 1. Assessing cost overruns

It may be considered surprising that neither the Project Management Body of Knowledge (PMI, 2013) nor the Association of Project Management (APM, 2016) provide a definition for 'cost overruns' or 'cost over-budget', presumably assuming that its meaning is straightforward and its calculation clear. However, it is argued in this paper that, especially in the situations where the development of a project is long and complex (Locatelli *et al.*, 2014), the assessment of cost overruns can be challenging.

The authors firstly review how cost overruns are calculated in the literature. Secondly, they propose a way to assess cost overruns in a rigorous and transparent way, especially in the cases where the number of projects is low and publicly available information is scattered, as is the case with megaprojects.

The UK's nuclear decommissioning programme is then used as an example application. Indeed, since nuclear decommissioning involves the management of radioactive material, nuclear decommissioning projects are highly uncertain, complex and long projects that involve several internal and external stakeholders (Invernizzi *et al.*, 2017a).

Finally, the authors reflect on the importance of highlighting the assumptions adopted during the appraisal of cost overruns.

2. Traditional assessment of cost overruns

Cost overruns are traditionally calculated in absolute terms as in Equation 1 and in relative terms as in Equation 2.

$$\text{Cost overrun [currency]} = C_{\text{end}}\text{ [currency]} - C_{\text{initial}}\text{ [currency]} \quad (1)$$

$$\text{Cost overrun [\%]} = \frac{(C_{\text{end}}\text{ [currency]} - C_{\text{initial}}\text{ [currency]})}{C_{\text{initial}}\text{ [currency]}} \quad (2)$$

In Equations 1 and 2, C_{end} refers to the actual cost – that is, the costs determined at the time of completing a project – and C_{initial} refers to the original estimated cost. Equation 2 reflects the 'project cost growth' metric presented by US construction research body the Construction Industry Institute (CII, 2016) and below in Equation 3.

$$\text{Project cost growth} = \frac{(\text{Actual total project cost} - \text{Initial predicted project cost})}{\text{Initial predicted project cost}} \quad (3)$$

However, even if it is a crucial point, few authors clarify the project stages (e.g. the points in time in the life cycle) and the sources to which the cost figures refer for the assessment of cost overruns. For instance, consider a 10-year project in a country with 3% inflation: the impact of inflation alone would be (1 + 0·03)10 = 1·334 – that is, an increase of 34%. The reference year for 'cost estimation' is therefore fundamental to understanding if the project is over budget (Lind and Brunes, 2015).

Recently, Awojobi and Jenkins (2016) stated that the values for 'estimated' costs for World Bank hydropower projects were based on information documented at the approval stage of the projects, most of which can be found in the bank's staff appraisal reports, while the values for 'actual' costs were determined by information at the end of construction in the bank's implementation and completion reports.

In 2002, Flyvbjerg *et al.* (2002: p. 5) defined actual costs as the 'real, accounted construction costs determined at the time of project completion', while estimated costs denoted the budgeted or forecasted construction costs 'at the time of decision to build'. 'Although the project planning process varies with project type, country and time, it is typically possible for a given project to identify a specific point in the process as the time of decision to build' (Flyvbjerg *et al.*, 2002: pp. 5–6).

Nevertheless, especially for long projects in the public sector, it is likely that multiple changes occur over time (Flyvbjerg *et al.*, 2002), which affects the definition of 'original estimates'. Cantarelli *et al.* (2010: p.4), quoting Cantarelli *et al.* (2009), highlight that 'the estimated costs at the real decision to build are usually lower than those at later stages of the decision-making process', which is a situation called 'lock-in', and that 'references to the formal decision to build do not always provide an accurate picture of cost overruns' (Cantarelli *et al.*, 2010: p. 38). Merrow (2011) defines C_{initial} as the 'estimate made at the full-funds authorisation' and suggests evaluating cost overruns through a systematic collection of a large number of cases, calculation of cost overruns of single projects and the definition of a threshold (25%) to determine the actual cost overruns.

Sloan *et al.* (2014), who describe cost overruns as the incongruence between initial estimates and final estimates, take another step forward specifying that costs can be evaluated 'after or during the delivery of a project (Sloan *et al*., 2014: p. 19)'. This shows a remarkable difference with the other publications shown in Table 1, as the authors argue that cost overruns can be calculated when the project is not finished but it is still ongoing. Similarly, Locatelli *et al.* (2017a: p. 262) define C_{end} as the 'final cost' or as the 'last estimate available for those [projects] still under construction'.

Additionally, CII (2016) emphasises the importance of mentioning 'according to whom' the initial estimates are evaluated. This is extremely important, since the project triangle of time–cost–quality originally adopted the contractor's perspective, so it is not clear if values refer to contractor cost or client price. Indeed, C_{initial} in Equations 1 and 2 represents for contractors the cost estimate used as a basis of the contract award, while for the client C_{initial} refers to the budget at the time of authorisation.

In summary, to assess cost overruns, most authors rely on the information on completed projects, where both the final costs and initial estimates 'at the time of the decision to build' are also available. However, they rarely highlight the boundary conditions and the assumptions regarding which point in time C_{end} and C_{initial} refer to and give limited attention to the provenance of the selected values of C_{end} and C_{initial}. This limits the research in infrastructure sectors where projects are particularly long, complex, affected by scope changes and subsequent new baselines, the number of completed projects is low and/or the information is widely dispersed. In these cases it is often not clear how to define C_{end} and C_{initial}, and this affects the calculation of cost overruns.

3. How to define and assess cost overruns

Cost, time and quality are the three measures traditionally used for assessing project management constraints. Quality comprises a broad range of topics (safety and security, environmental constraints, socio-economic aspects, stakeholders' expectations, etc.) and can be assessed at different points in time and according to a number of different stakeholders involved in the project's development (Davis, 2014; Turner and Zolin, 2012).

Time is sometimes argued to be a better indicator of project performance than cost, being 'more visible', harder to be manipulated and a driver for cost itself. However, cost does not necessarily have a linear relationship with time – and cost overruns attract significant attention. But as cost overruns can be hard to define, this research suggests how to assess them transparently and ultimately compare them. This is exemplified using the UK's nuclear decommissioning industry, but the reasoning is similar for other megaprojects and programmes.

Table 1. A review of definitions of cost overruns in the literature and of the variables C_{end} and $C_{initial}$ used to calculate them

Reference	Definition of cost overruns	Absolute or relative	C_{end}	$C_{initial}$
Jadhav *et al.* (2016)	Cost overruns are defined as 'the difference between forecasted and actual construction costs'	Absolute	C_{end} refers to 'actual costs'	$C_{initial}$ refers to the 'budgeted amounts'
Brookes and Locatelli (2015) and Locatelli *et al.* (2017b)	Projects were judged to be over budget, that is to suffer from cost overruns, when 'the final cost of the project was greater than the 110% of the original estimate (adjusted for inflation)'	Relative	C_{end} refers to the costs 'at the point at which the project entered operation'	$C_{initial}$ refers to the 'estimated costs', whose figures were taken at the time as close as possible to 'the first formal activity', such as 'the acquisition of any land rights required for the project'
Ansar *et al.* (2014)	Cost overruns refer to 'actual outturn costs expressed as a ratio of estimated costs'	Relative	C_{end} refers to 'actual outturn costs'	$C_{initial}$ refers to 'estimated costs', 'estimated budget' and/ or 'initial budget'
Sloan *et al.* (2014)	Cost overruns 'insinuate the incongruence of initial estimates with final estimates, after or during the delivery of a project'	Absolute	C_{end} refers to 'final estimates' both at the end and during the development of the project	$C_{initial}$ refers to 'initial estimates'
Merrow (2011)	Cost overruns are measured as 'the ratio of the actual final costs of the project to the estimate made at the full-funds authorisation'	Relative: although not explicit in the definition, cost overruns are calculated as a percentage of the estimated costs	C_{end} refers to the 'the actual final costs'	$C_{initial}$ refers to the 'estimate made at the full- funds authorisation'
Cantarelli *et al.* (2010)	Cost overruns are calculated as 'actual out-turn costs minus estimated costs as a percentage of estimated costs'	Relative	C_{end} refers to actual costs, where 'actual costs are defined as real, accounted construction costs determined at the time of project completion', as in the paper by Flyvbjerg *et al.* (2002)	$C_{initial}$ refers to estimated costs, where 'estimated costs are defined as budgeted or forecast construction costs determined at the time of the decision to build', as in the paper by Flyvbjerg *et al.* (2002)
Odeck (2004)	Cost overruns refer to 'difference between actual and estimated cost'	Absolute	C_{end} refers to the 'actual cost'	$C_{initial}$ refers to the 'estimated cost'
	'Ratio of actual to estimated cost in %'	Relative		
Flyvbjerg *et al.* (2002) and Flyvbjerg (2008)	Cost overruns are calculated as 'actual costs minus estimated costs in per cent of estimated costs'	Relative	C_{end} refers to actual costs, where 'actual costs are defined as real, accounted construction costs determined at the time of project completion'	$C_{initial}$ refers to estimated costs, where 'estimated costs are defined as budgeted or forecasted construction costs determined at the time of the decision to build'

Nuclear decommissioning consists of all the administrative and technical actions to remove all the regulatory controls from a facility and restore the site to new use (IAEA, 2017). Globally, nuclear decommissioning cost estimates lie in the range of hundreds of billions of pounds, reaching £55 billion in France (WNA, 2015) and over £163 billion in the UK (NDA, 2017a) (Figure 2). Moreover, cost estimates for nuclear decommissioning are extremely challenging (Torp and Klakegg, 2016) and keep increasing. This is partially due to the fact that the number of completed decommissioning projects is negligible compared to new build, therefore there are limited data regarding cost estimation. In the nuclear industry, more than 500 nuclear power plants were built during the twentieth century while only 16 have been fully decommissioned (OECD NEA, 2016).

The following points are recommended to assess cost overruns.

Figure 2. The UK's nuclear decommissioning programme is currently estimated to cost in excess of £163 billion over the next 120 years (courtesy Magnox)

3.1 Define when $C_{initial}$ refers to

First of all, clearly state which are the points in time in the project life cycle that $C_{initial}$ refers to. The 'original' estimated costs at the start of the project might not be available, or might not even exist. It is fundamental to highlight the assumptions underpinning the selection of the point in time that $C_{initial}$ refers to. This is the case for the decommissioning of some nuclear sites, such as Sellafield in the UK (Sellafield Ltd, 2016) (Figure 3), where the fuel-reprocessing operations of the site are so intertwined with those of decommissioning that it is extremely hard to draw a line between the two. In this case, these 'original' estimates can be defined arbitrarily, but the reasons for this decision have to be clearly stated.

For instance, the first publicly available information regarding the 'original' decommissioning cost estimates for Sellafield dates back to 2005 – that is, when the UK Nuclear Decommissioning Authority was established (NDA, 2017b) – so these estimates can be taken into account to define Sellafield's $C_{initial}$.

3.2 Define when C_{end} refers to

Secondly, clearly state which is the point in time that C_{end} refers to. This can be challenging because the 'final' actual costs at the end of the project might not be available, or might not even exist yet. This is the case for very long projects that last several decades and/or have yet to reach a conclusion. This is also the case for the decommissioning of Sellafield and for other construction projects such as the bridge on the Strait of Messina in Italy (Rogers, 2015).

The Messina crossing has been a political debate in Italy for a generation: a company was set up to build the bridge in the 1980s and detailed design work was carried out in the 1990s (Leto, 1994), but the project was cancelled in 2006. The bridge is now back on the Italian agenda (Rogers, 2015). In such situations the final actual costs are not available, as the project is not yet complete. However, the estimate at completion – that is, 'the expected total cost of completing all the work expressed as the sum of the actual cost to date and the estimate to complete' (PMI, 2013: p. 539) – can be used instead. This has to be clearly stated to define C_{end}.

3.3 Define who defines $C_{initial}$ and C_{end}

Clearly state by whom C_{end} and $C_{initial}$ are defined, being aware of the difference between cost and price when assessing cost overruns. One stakeholder's price is another stakeholder's cost and talking about 'cost overruns' only makes sense if the viewpoint of one particular stakeholder is highlighted.

Price is defined as a sum the contractors' costs plus a mark-up. In very simple terms, in a fixed-price or lump-sum contract, the risks are assigned to the contractor, which is expected to request a higher mark-up to cover uncertainties. In this situation, if the actual costs for the contractor increase and cost overruns occur, the mark-up is eroded (potentially becoming negative, resulting in a loss for the contractor), but the client is not affected by the cost overruns.

Conversely, in a cost-reimbursable or cost-plus-fee contract, contractors are reimbursed by the client for the actual cost of performing the work, plus a mark-up. In this situation, if the actual costs for performing the work increase compared to the budgeted ones, the owner is directly affected by the cost overruns as the price rises. In other cases, stakeholders create a temporary organisation, called special purpose vehicle (Sainati *et al.*, 2015), that further complicates the difference between price and cost.

Moreover, for major and megaprojects, estimates are made summing up sub-project cost estimates. These sub-projects

Figure 3. Decommissioning costs at Sellafield are intertwined with fuel-reprocessing costs, making analysis complex (courtesy Sellafield)

estimates refer to the price that will be paid to the contractors and not the actual costs of the work to be done. This price is normally higher than the cost of work to guarantee a mark-up for the contractors. However, it may be lower for strategic reasons, for example to gain first-mover advantage, or when the actual profit is not made by the selling of the product itself, but of the products and services that the client will need after having bought the first item. This works at all scales – from ink cartridges for printers to uranium for nuclear power plants.

On the latter topic, Anne Lauvergeon, former chief executive officer of French nuclear firm Areva, stated in 2008 that the model of the CEA, a French public government-funded research organisation, was indeed following the model of coffee machines and coffee capsules (Challenges, 2008). Therefore, it is pivotal to clarify 'according to whom' C_{end} and $C_{initial}$ are defined.

3.4 Define which stage of the development $C_{initial}$ and C_{end} refer to

It is also important to highlight which stage of the development of the project the estimates refer to (e.g. concept screening, detailed design, construction) and what is the degree of uncertainty associated to it. Different project stages present different uncertainty levels (GIF, 2007) and probability P50 estimates are significantly different to P80 estimates (HM Treasury, 2015).

Some uncertainties are caused by known unknowns, so they cannot be dealt with up front. Others can be mitigated at an early stage of the project development, such as the specification employed at the procurement stage to share the risk of delays in the supply of equipment and services.

For example, during decommissioning of the Rocky Flats former nuclear weapons plant in the USA (Invernizzi *et al.*, 2017b), shared responsibility between the US government and contractors helped to avoid delays in delivery of products and services and ultimately avoided cost overruns (Cameron and Lavine, 2006).

3.5 Scope changes and baselines

Scope changes and new baselines should be identified, highlighting the different contractual agreements that can influence project performance (Suprapto *et al.*, 2016). Scope changes refer to any change to the project scope; these almost always require an adjustment to the project cost or schedule. Scope creep is the uncontrolled expansion to product or project scope without adjustments to time, cost and resources (PMI, 2013).

When scope creep occurs, the additional costs are mostly sustained by the contractor, which might have a limited understanding and visibility of the overall economic impact of accommodating all the clients' requirements. On the other hand, scope changes are dealt with in different ways depending on the type of contract agreement. In fixed-price contracts, changes in scope are accommodated generally with an increase of the contract price, while in cost-reimbursable contracts, the client has the flexibility to re-direct the contractors whenever the scope of work could not have been precisely defined at the beginning (PMI, 2013). This means that, if scope changes are agreed by both parties under a reimbursable contract, scope changes change the 'original estimates' and costs are re-baselined without causing an increase of the cost overruns, only an increase of the overall project cost.

Moreover, Lind and Brunes (2015) have summarised the causes of scope changes (e.g. changes in the design, in the production function, in the price of the factors of production, and due to inefficiencies), highlighting the importance of clustering them according to the different phases of the project development in which they occur and the cost overruns they cause. Unforeseen ground conditions are also a source of dispute (Fender-Allison and McEwen, 2017; Osborne Clarke, 2015).

In summary, it has to be emphasised to which baseline $C_{initial}$ refers when calculating cost overruns, and the assumptions that underpin the selection of this particular point in time. For example, in the nuclear industry, scope changes might be triggered by external events that cause changes in the regulations – such as following the 2011 Fukushima accident (Inokuma and Nagayama, 2013).

3.6 Define financial assumptions for assessment

Lastly, it is important to state clearly the financial assumptions for assessment of cost overruns. Inflation, discount factors to model the cost of financing the business activities, assumptions regarding the currency and fluctuations in exchange rates can all affect costs significantly.

Again, taking the example of decommissioning, OECD NEA (2010: p. 58) affirms that, 'a one-half percent change in either inflation/escalation or discount rate has a far greater effect on long-term costs than any single cost driver'.

4. Conclusion

Cost overruns have always attracted attention, particularly on larger publicly funded infrastructure projects. Where projects are long, complex and affected by scope changes and new baselines, the assessment and comparison of cost overruns can be extremely challenging.

This paper reviews literature on cost overruns and presents a way to address the challenges in assessing them. In particular, it is important state clearly the assumptions concerning the point in time that initial and final cost refer to, the point of view that is adopted, the scope changes and the financial aspects. This enables transparent and rigorous assessment of cost overruns, which is particularly important in the case of major public-sector projects and programmes such as nuclear decommissioning.

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D.2 Work done in relation to this PhD research but not included in the main body of this thesis

D.2.1 Papers published in international peer-reviewed Journals not included in this thesis

1. Invernizzi, D.C., Locatelli, G., Brookes, N.J., 2017, "How benchmarking can support the selection, planning and delivery of nuclear decommissioning projects", Progress in Nuclear Energy, 99, pp.155–164.
2. Locatelli, G., Invernizzi, D.C., Brookes N.J., 2017, "Project characteristics and performance: an empirical analysis for large transport infrastructure projects", Transportation Research Part A: Policy and Practice, 98, pp.108–122.

D.2.2 Presentations in conferences and workshops not listed in Scopus

1. Invited presentation at the Environment Agency, Penrith (UK), 22nd January 2019:
    - *"Benchmarking nuclear decommissioning: an exploration of the relationship between nuclear decommissioning projects characteristics and cost performance"*
2. Presentation at the International Research Network on Organizing by Projects (IRNOP), Melbourne, Australia, December 2018, of the paper "Decommissioning Projects in Europe: What Can the Offshore Oil & Gas and Nuclear Industries Learn from Each Other?", by Invernizzi, D.C., Locatelli, G., Love, P. E. D., Brookes, N.J.
3. Invited presentation at the CRA (Corporate Risk Associates) forum, held in Holmes Chapel (UK), on the 25th and 26th of September 2018:
    - *"What Makes a Nuclear Decommissioning Project Successful? (How benchmarking will help your company)"*
2. Invited presentation at "9th International Summer School on Nuclear Decommissioning and Waste Management, Joint Research Centre (JRC), Ispra (Italy), 13th-14th June 2018:
    - *"Managing Social Challenges in the Nuclear Decommissioning Industry: a Responsible Approach Towards Better Performance"*

3. Invited presentation at the "Technical Meeting Funding for Waste Management and Decommissioning", held in Vienna, 9th-12th June, 2018:
    - *"Cost overruns – helping to define what they really mean"*
4. Presentation of the paper "Bridging Qualitative and Quantitative Analysis to Investigate the Infrastructure End-of-Life: the Case of Nuclear Decommissioning", by Invernizzi, D.C., Locatelli, G., Brookes, N.J., 2018, in the 9th International Business Workshop, in June 2018, Leeds.
5. Invited presentation at the 9th Annual Nuclear Decommissioning & Waste Management Conference Europe, Manchester, 24-25 May 2018:
    - *"What makes a Nuclear Decommissioning Project Successful? (How benchmarking will help your company)"*
6. Presentation at the Postgraduate Conference for the School of Civil Engineering (Leeds), 21rst-22nd of March 2018 – 1rst place award:
    - *"What makes a Nuclear Decommissioning Project Successful? A Cross-Comparison"*
7. Presentation of the paper "*A methodology based on benchmarking to learn across megaprojects: the case of nuclear decommissioning*", by Invernizzi, D.C., Locatelli, G., Brookes, N., at EURAM 2017, Glasgow, 21-24 June, Paper selected for Journal Publication**.**
8. Presentation at the Risk Perception, Communication and Ethics of exposures to Ionizing Radiation (RICOMET) conference, Vienna, 27th-29th June 2017:
    - *"Managing Social Challenges in the Nuclear Decommissioning Industry: a Responsible Approach Towards Better Performance"*
9. Presentation at Engineering Project Organization Conference (EPOC), Stanford Sierra Camp, Lake Tahoe, CA, USA, 5th – 7th June 2017:
    - *"Robust methodology to learn across Megaprojects"*
10. Invited presentation at the 8th Annual Nuclear Decommissioning & Waste Management Conference Europe, Manchester, 24-25 May 2018:
    - *"Managing Social Challenges in the Nuclear Decommissioning Industry: a Responsible Approach Towards Better Performance"*
11. Invited presentation at the OECD/NEA 35th meeting of the Co-operative Programme for the Exchange of Scientific and Technical Information

Concerning Nuclear Installation Decommissioning Projects CPD Management Board, Paris, October 2016:

- *“What is a successful Nuclear Decommissioning Project – and what makes it successful?”*

12. Presentation at the World Nuclear Decommissioning and Waste Management Congress, London, September 2016:
    - *“Do you know what makes your decommissioning project successful?”*
13. Presentation at the First Annual Meeting of the Coordinating Work Group “Data Analysis and Collection for Costing of Research Reactor Decommissioning” (DACCORD Project - Phase 2) at the International Atomic Energy Agency (IAEA) - Vienna, 29th August - 2nd September 2016:
    - *“Benchmarking nuclear decommissioning”*
14. Presentation at the IAEA “International Conference on Advancing the Global Implementation of Decommissioning and Environmental Remediation Programmes”, Madrid, 23rd to 27th May 2016 and participation to the site visit to Jose Cabrera, a Spanish NPP that is currently in the final stage of decommissioning:
    - *“How benchmarking can support the selection, planning, and delivery of nuclear decommissioning projects”*
15. Presentation at the “4th International Mega-Project Workshop: theory meets practice”, LUISS (“Libera Università Internazionale degli Studi Sociali”, i.e. "Free International University of Social Studies") Business School, Rome, 19th and 20th May 2016:
    - *“End of operations, beginning of a new megaproject: the new challenge of project management”*
16. Presentation of the PhD research methodology and results at the “University Nuclear Technology Forum (UNTF)”, Sheffield, 5th - 7th of April 2016:
    - *“Benchmarking Analysis & Nuclear Decommissioning”*
17. Presentations at the University of Leeds throughout the year, November 2015 – July 2018, as part of the “nuclear PhD group”.

D.2.3 Other work done

1. Dissertation prepared for the International School of Nuclear Law (ISNL 2018), organized by the OECD/NEA, Montpellier, France: entitled "*Regulatory challenges of nuclear decommissioning projects: The project managers' point of view*" (Invernizzi, D.C., 2018).
2. Rapporteur for the OECD/NEA as part of the International Expert Feedback group. The final report was entitled "T*he Methodology of Cost Estimation for Decommissioning Nuclear Facilities in the Russian Federation - International Expert Feedback on the Methodology Developed by ROSATOM*" and it is publicly available at https://bit.ly/2QdGSxu.
3. Invernizzi, D.C., Locatelli, G., section in "*Decommissioning nuclear power plants in Europe lessons learned: improving efficiency*", whitepaper, Nuclear Energy Insider (NEI), 2018.
4. Review for the editorial project manager of Woodhead Publishing Limited of the first edition of the book "Nuclear Decommissioning: Planning, Execution and International Experience" edited by Michele Laraia, October 2015.
5. Peer reviews of scientific articles for the following Elsevier Journal, listed in Scopus:
    - Energy
    - International Journal of Project Management
    - Progress in Nuclear Energy
    - Journal of Environmental Radioactivity
    - Project Management Journal

D.2.4 Grants won

1. University of Leeds, Civil Engineering, travel grant to participate to the International Research Network on Organizing by Projects (IRNOP), Melbourne, Australia, 2018.
2. OECD/NEA travel grant to present during the OECD/NEA "Decommissioning Cost Expert Group", Paris, June 2018.
3. IAEA travel grant to participate to the "Technical Meeting Funding for Waste Management and Decommissioning", Vienna, June 2018.

4. IAEA travel grant to participate and present to the meeting on 'Data Analysis and Collection for Costing of Research Reactor Decommissioning (DACCORD) Project – Phase II', held in Sydney, Australia from 27 to 31 March 2017.
5. IAEA travel grant to participate to the 10th meeting of the International Decommissioning Network (IDN), Vienna, 29th-1st December, 2016.
6. OECD/NEA travel grant to present during the OECD/NEA 35th Meeting on Nuclear Decommissioning, Paris, on the 9th of November 2016.
7. OECD/NEA travel grant to participate as a rapporteur to the "International Expert Feedback (IEF) of the methodology of cost estimation for decommissioning nuclear facilities in the Russian Federation", Moscow, 26th – 30th September 2016.
8. IAEA travel grant to participate to the "International Conference on Advancing the Global Implementation of Decommissioning and Environmental Remediation Programmes", Madrid, May 2016.
9. Travel grant from the Thailand Institute of Nuclear Technology to participate to the Association of Southeast Asian Nations (AESAN) Workshop on Nuclear Power Plant Safety Research, Hanoi, Vietnam, 10th-12th May 2016.
10. Short Term Scientific Mission (STSM) research grant to participate to the MEGAPROJECT COST ACTION - TU1003, University of Lincoln, (UK), April 2015.

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