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

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. Their costs keep increasing, while there is a limited understanding of why this happens. Nuclear Decommissioning Projects and Programmes (NDPs) are the unit of analysis of this paper, due to the relevance of this sector and the number of public information available.

The aim is to identify the NDP characteristics mostly impact on the NDP performance in term of cost and time. Findings from the application of content analysis on the information collected through 35 interviews with senior practitioners highlight the importance of several NDP characteristics, including the need to have detailed knowledge of the site conditions, a good relationship with the regulatory authorities, the availability of storage facilities and stable funding.

Keywords

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

Introduction

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 given 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 also involves the construction of new facilities, e.g. to treat and store the waste material arising during de-construction.

Decommissioning is a new, emerging, global challenge that project practitioners and academics need to understand and tackle. Indeed, as there are fundamental differences between construction and decommissioning projects, it is reasonable to assume that the characteristics that affect their cost and time performance could also present significant differences.

Indeed, as there are fundamental differences between construction and decommissioning projects. Decommissioning projects typically face several challenges, including (Invernizzi, Locatelli, and Brookes, 2017a, 2019a; Volk *et al.*, 2019):

- insufficient funding set aside for decommissioning during the planning and operation stage;
- management of ethical and intergenerational concerns as long-term liabilities may be created;
- issues with personnel transaction as the workforce often has to take part in decommissioning their own source of jobs.

Additionally, traditional project motivations are missing because at the end of a decommissioning project:

- there is no cash in-flow;
- no revenue-generating assets are created;
- no 'landmark infrastructures' are built (conversely, these are destroyed);
- a net reduction in opportunities for employment – i.e. redundancies – is created.

Hence, the motivation for planning and delivering decommissioning projects are radically different from traditional construction projects and megaprojects (for example, the ones described by Merrow (2011)). Consequently, as discussed in the "research background" section, it is reasonable to assume that the characteristics that affect their cost and time performance could also present significant differences.

In the project management literature, the "success" of construction projects has been extensively investigated, as presented in 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 minimal research on "success factors" in decommissioning.

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, the decommissioning of infrastructure (such as nuclear and oil & gas facilities) has been emerging (and is rapidly growing) only since the last couple of 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 (Lam, Chan, and Chan, 2008; Williams, 2016; Zavadskas *et al.*, 2013), 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 and Gas Authority, 2017), while for the UK government the cost of cleaning up Britain's historic nuclear sites is between £99 billion and £225 billion over the next 120 years. The clean-up of the biggest UK site undergoing decommissioning, i.e. Sellafield site, reach £160 billion (Gov.UK, 2019). Unfortunately, despite the technical expertise, the decommissioning costs globally keep increasing. For example, the total discounted nuclear liabilities declared in the UK Nuclear Decommissioning Authority (NDA) 2011/2012 Annual Report for Sellafield was "£37 billion (NDA, 2011). In just a few years, the cost of decommissioning the Sellafield nuclear site increased four times. The cost increase in Sellafield alone is, therefore, more than the total budget of High Speed 2 (£56b), Crossrail (£16b), Hinckley Point C (£20b) and Thames Tideway Scheme (£5b) combined. This demonstrates that the decommissioning challenge can be considered one for the biggest megaprojects challenge in the UK and, to the best of the authors' knowledge, globally.

The focus on the Nuclear Decommissioning Projects and Programmes (NDPs), intended as site-level endeavours, is justified primarily due to the economic relevance of this sector, and the number of publicly available information. More specifically, the scope is the analysis of commercial European NDPs, primarily because of the greater homogeneity in regulations and the availability of information.

More specifically, the research addresses the following research question:

- *Which NDP characteristics mostly impact on the NDP performance in term of cost and time*?

Also unlike the more traditional project management research on "success", the authors use the terms "characteristics" and "performance" in place of the more common "success factors" and "success criteria". This is mainly due to the exploratory nature of the research and to avoid giving 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 paper is structured as follows: the "research background" contraposes the vast research on success factors in project management research (particularly in the construction industry), with the minimal project management literature on decommissioning projects. This allows highlighting the gap in knowledge about the end-of-life of infrastructure and the need and urgency to investigate NDPs. The "method" shows how the knowledge gap was addressed and explains how primary data and information were collected and analysed through content analysis. This allowed coding of the characteristics that affect the NDPs' cost and time performance, as explained in the "research findings" section. The "discussion" section reflects on these findings in light of the existing literature and provides critical guidelines for practitioners. The "conclusions" provide a summary of the key research findings envisaging a cross-sectoral sharing of lessons learned.

Research Background

This section has 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 the 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. These two subsections introduce the most relevant differences between construction and decommissioning projects. These differences underpin the proposition investigated, that the characteristics affecting the cost and time performance of decommissioning projects present relevant differences from a traditional construction project. These differences underpin the idea investigated, that the characteristics affecting cost and time performance in decommissioning projects are different from traditional construction projects.

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 and Müller, 2005)). Providing one of the earliest literature reviews 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 and 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 (de Carvalho, Patah, and de Souza Bido, 2015; Mir and Pinnington, 2014; Müller and Turner, 2007), project governance (Joslin and Müller, 2016), knowledge management (Jennex, 2006), etc.

Focusing specifically on the construction industry (due to the dichotomy construction/decommissioning and as a well-investigated research context), several studies have focused on "project success" and investigated what effect 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. Locatelli et al. (2017a) focused on megaprojects. 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 factors and failure factors from a list of selected publications, concluding that knowledge sharing and communication are essential 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 critical aspects for the successful planning and delivery of a nuclear programme, concluding that the standardisation of the design and supply chain availability is essential. Sainati et al. (2019) discuss the critical role of regulations as a barrier to project financing.

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.

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 wholly or partially 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 demanding 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 and 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 and 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 taxpayers' money), while the benefits provided by the infrastructure were exploited by past generations (Taebi, Roeser, and van de Poel, 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, Torp and Klakgg (2016) explore the challenges of cost estimation in an uncertain environment. 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) and Mignacca et al. (2020) underline the importance of early preparation for decommissioning and highlight the importance of:

- Build a decommissioning team composed of both plant staff and specialists;
- Insist on pre-work and on a thorough radiological characterization[1];
- Develop a tailored "decommissioning manual";
- Replace the plant's legacy support systems with modular systems fit for decommissioning.

[1] 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)

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, 2016), the OECD/Nuclear Energy Agency (NEA) (OECD/NEA, 2012, 2015, 2016), the European Commission (EC, 2018), the European Court of Auditors reports (2016; 2011) and others (e.g.(Laraia, 2012; Öko-Institut, 2013; Wuppertal Institute, 2007)). 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, 2010, 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, 2012). However, a European-wide study on the NDP characteristics that affected the NDP performance is still missing, and due to the growing number, size and cost of NDPs need to be urgently performed. The research addresses this gap in knowledge, and the above-mentioned practitioner-based publications consist of the most relevant source of information to understand the research context.

Method

Justification of using interviews to address the challenges of researching NDPs

The research method to investigate NPD needs to deal with a number challenges: first of all, at a global level, there are very few completed NDPs (e.g. 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 minimal and unstructured, and reporting procedures are hardly comparable in different countries. These data and information consist of a mix of quantitative and qualitative data; usually, the latter being more comprehensive and exhaustive than the first (Yin, 2009). So, this inhomogeneous reporting makes it difficult to systematically analyse these secondary data and information.

Considering an exploratory research context, interviews were selected as a suitable method to investigate NDPs, primarily due to the amount and quality of information that interviews allow to collect (as interviewees value more highly personal interaction than an anonymous questionnaire and are therefore more willing to provide detailed answers), and the possibility for the interviewer to ask for clarification about the interviewees' answers during the interviews (decreasing the chance of misunderstandings) (Saunders, Lewis, and Thornhill, 2009).

Selection of the interviewees

In Europe, there are currently a small but growing number of NDPs (IAEA, 2018). Invernizzi et al. (2019) identified 29 NDPs for which information estimates at completion are available in time. These are: Berkeley, Bradwell, Chapelcross, Dounreay, Dungeness A, Harwell, Hinkley Point A, Hunterston A, Oldbury, Sellafield, Sizewell A, Trawsfynydd, Wylfa and Winfrith in the UK; Chinon A, Chooz A, Brennilis, Bugey – 1, St. Laurent, Super-Phoenix (Creys-Malville) in France; Vandellos – 1 and Jose Cabrera in Spain; Greifswald NDP in Germany; Kozloduy 1-4 in Bulgaria; Ignalina in Lithuania; and Trino (Enrico Fermi power station), Caorso, Latina and Garigliano in Italy.

The interviewees were selected through purposive sampling (Palinkas et al., 2015), primarily according to their involvement and experience in at least one of the abovementioned European NDP. Moreover, interviewees were selected according to their seniority, their role in the NDP and their international experience. For these reasons, also practitioners from Finland, Switzerland and the Netherlands were contacted. In other words, more senior and experienced practitioners with management experience in international NDPs across Europe were selected first.

The authors sent 75 emails to invite the senior practitioners involved in decommissioning projects across Europe. Ultimately, 35 interviews were scheduled and conducted, for a rate of response of 46.7%. In total, 29 interviewees had more than ten years in the industry. 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. At least one interviewee per NDP listed above was interviewed, with the exception of Sellafield, as Sellafield accounts for more than 70% of the UK overall budget (NDA, 2018) and was therefore excluded as an outlier. The interviewees covered the following countries: UK, France, Italy, Spain, Germany, Lithuania, Bulgaria, Slovakia, Sweden, Finland, Switzerland and the Netherlands.

Description of the interview process

Interviewees were contacted via email and were asked to be interviewed about the following question: "*In your opinion, which NDP characteristics mostly impact on the NDP performance* *in term of cost and time*?". Such a question was sent to the interviewees at the same time as the invitation.

The question was the focus of the discussion during the interview and had the aim 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 interviewer used personal judgment to ask follow-up this question to clarify the interviewees' comments. Of the 35 respondents, three preferred to email their answers 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 anonymity. 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 valuable, especially when the permission to record was not granted by the interviewee (only one case). The overall interviews were forecasted to last 30 to 40 minutes, but eight interviews lasted more than one hour, as some interviewees provided more detailed and lengthy answers. The average duration of the interviews was 45 minutes.

Analysis of the interview

All the interviews were thoroughly transcribed by the interviewer. 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 software package that supports qualitative analysis by facilitating the categorization of information into different clusters and sub-groups. NVIVO11 has been selected because it allows to collect, manage, and analyse a large number of qualitative information (in this case, collected from the 35 interviews) in a systematic way. After the transcription, the interviews were uploaded in NVIVO11 and each section of the interview that discusses a different topic was highlighted. This allowed the creation of preliminary codes to cluster the different topics highlighted. The initial categorization was then refined in several iterations to finalize the coding for the data analysis, on the basis of (DeCuir-gu and Mcculloch, 2011; Elo and Kyngäs, 2008; Olawale and Sun, 2015), and following the recommendations for the preparation and analysis of data by (DiCicco-bloom and Crabtree, 2006; Mclellan-Lemal and Macqueen, 2003). Discussion among colleagues also supported the finalization of the coding. In this way, the transcribed material was systematically analysed on the basis of content (Dixon-Woods *et al.*, 2005; Hsieh and Shannon, 2005; Kohlbacher, 2006). Table 1 summarises how the code " Limited clarity of the waste routes and availability of storage and disposal facilities " was derived through discussion and iterative coding, similarly to what was recently exemplified by (Invernizzi et al., 2019).

<table>
<tr><td>Extract from the interviews</td><td>Preliminary coding and identification of sub-category</td><td>Final coding</td></tr>
<tr><td>"...and then there's another topic that's related to the availability of the waste streams, as not all waste channels are open. So there is some rubbish that we do not know how to ship [...]"</td><td>Availability of waste routes and clear understanding of how to handle all the different types of waste</td><td rowspan="3">Limited clarity of the waste routes and availability of storage and disposal facilities</td></tr>
<tr><td>"[another challenge are the] waste management options, i.e. the existence of usable, cost-effective, flexible waste solutions both LLW and ILW, transport and packaging."</td><td>Clear understanding of the different waste management options available, including packaging and transport</td></tr>
<tr><td>"And the second point is [...] the non-availability of a final disposal to place our waste, so we have also additional costs for prolongation of things on our site [...]"</td><td>Non-availability of a facility where to ship the waste for long term storage or disposal</td></tr>
</table>

Table 1. Example of the iterative coding process."

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 to 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 critical 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 endpoint 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 is 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 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 the 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 result into additional scope when we come in...we may find asbestos that we haven't foreseen being in an area of the site!*".

Overall, the fact that often NDPs are "first of a kind", due to the wide variety of designs, the different purposes that the nuclear facilities served, their unique operational history, and the minimal number of completed NDPs worldwide is a relevant challenge. In fact, this might lead to over-engineering of solutions, which affect not only NDPs but also the overall nuclear industry, causing cost-overruns.

Limited clarity of 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 affects 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 refuelling 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 scrabbling 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 is affected.

The following comment exemplifies this issue: "*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 with 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 readily 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 characteristic 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".*

Interviewees also emphasised the importance of incentives schemes to promote work adhering to deadline and deliverables. Other interviewees stressed the overall complexity of the governance, as an NDP characteristic 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).

The need for early planning

Early and detailed planning was also mentioned as relevant NDP characteristics 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!".* Moreover, the interviewees explained that the design of the nuclear facility, completed with no thought about decommissioning in mind, hinders its decommissioning. So, for example, several parts of the facility that need to be decontaminated and decommissioned are extremely hard to reach, as their design was optimized for the plant construction and operations but not for its decommissioning.

The benefits of using a "program-based" approach during project planning, i.e. the management of NDPs in different locations, promoting the sharing of lessons learned across NDPs, was also mentioned. One interviewee, for instance, explained: "*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 by 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.

Also concerning the NDP planning is the comment about the need to exploit pilot projects and mock-ups, i.e. the testing and training of a project activity off-site before it is performed on-site, which facilitates the training of the employees before entering the nuclear site, ultimately reducing the costs of on-site operations, as they can be completed more effectively. 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: "*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!"*.

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*!". Interviewees referred to specific resources needed for a specialized piece of work, such as resources specialized in high-voltage welding and trained to work on nuclear sites, but also mentioned the lack of project management experience, expressing frustration, e.g. by stating that one of the most critical NDP characteristics 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*". Interviewees also highlighted the (high) costs of the above-mentioned qualified resources.

Limited clarity of the final end-state

Furthermore, several interviewees highlighted their concerns about the lack of clarity of the site end-state and consequently limited scope definition of the NDP. The end-state of a NDP usually is 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 a 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 rebuild 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 characteristic 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".

Discussions

Contribution to Theory

One of the key theoretical contributions of this exploratory research is related to its context, i.e. the one of decommissioning and end-of-life projects. The extendibility of project theory to decommissioning projects has only very sparsely been previously investigated, and there is a rapidly growing need to fill this gap, not only in the nuclear sector but also concerning the end-of-life of other ageing infrastructure (power plants, bridges, etc.).

Characteristics of decommissioning projects shared with other projects

The first contribution to theory could be summarized as one of reinforcement, as the findings presented in previous publications (not related to decommissioning) emerge to be corroborated in the realm of NDPs. So, looking at the findings of current research through the lens of existing literature, it can be argued that also construction projects and megaprojects are affected by unknowns and uncertainties about the site conditions (Merrow, 2011), regulatory-related challenges (Sainati *et al.*, 2015), stable funding and overall political support (Locatelli *et al.*, 2017b), project planning (Caffieri *et al.*, 2018), etc. Consequently, decommissioning projects benefit from the existing knowledge to improve their planning and delivery as discussed in (Ramasesh and Browning, 2014). Engagement with both internal and external stakeholders (and the local community in particular) also emerged as pivotal, which is in line with recent works about the planning and delivery of megaprojects (Di Maddaloni and Davis, 2017; Wang *et al.*, 2017).

Characteristics "unique" for decommissioning projects

The key insight of the project management "success school" of thoughts (Turner, Anbari and Bredillet, 2013, p.17) need to be broadened to include "unique" characteristics that affect decommissioning projects. Stressing the uniqueness and exceptionality of these NDP characteristics beyond what can be elaborated by only examining the findings using the authors' background knowledge and existing literature is, however premature and could be misleading. Consequently, circumspection in formulating conclusive statement based on an exploratory results remains vital, and the following text aims to start a broader academic discussion rather than providing a holistic knowledge to explain decommissioning projects.

Among the NDP characteristics that have not been particularly stressed in construction projects, the authors identified the limited clarity of the final end-state of the decommissioning project and the limited clarity of the waste routes and availability of storage and disposal facilities. This is a challenge that construction projects do not often face, as there is normally a clear vision about the final purpose of infrastructure and only a very limited amount of problematic waste to deal with during its construction. This is a useful addition to previous considerations, as it highlights the importance to formulate a clear vision of the final site end-state of the decommissioning project and the need to carefully manage project interdependences (e.g. decommissioning and dismantling *projects* with waste management *operations*).

The characteristics that have not been stressed in studies about construction projects are present in decommissioning projects as decommissioning projects lack the traditional management-related motivations to effectively complete the project(s), which ultimately affect their timely and cost-efficient completion. These motivations are related to the absence of a revenue stream, and the vision of a future completed landmark infrastructure, which would create new job positions too.

It is also important to reflect upon the fact that different interviewees sometimes offered slightly contradictory perspectives, some highlighting the need of addressing the numerous uncertainties through early and systematic planning (considering the regulatory environment, the political environment, the supply chain, the technologies, etc.), others by underlining the need of adopting greater flexibility while managing these complex and long projects. The length of these projects, sometimes outlasting the career of the project manager and even of organizations dealing with them can also revive the discussion about project temporality (Brookes *et al.*, 2017).

Lastly, a further contribution to theory refers to the consideration that decommissioning projects need to be framed in a system lifecycle perspective that encompasses design, operations, and finally decommissioning, ideally including and embracing the circular economy paradigm (Mignacca *et al.*, 2020; Velenturf *et al.*, 2019).

Contribution to Practice

Focusing on the realm of European NDPs, the relevant practical contribution is offered to practitioners in the decommissioning industry, by making explicit the NDP characteristics that affect the NDP time and cost performance. This list is relevant both for project managers entering the nuclear-decommissioning industry, but also for more senior project managers already in the industry. This list could be used, for example, by project managers that want to increase their understanding of the European nuclear decommissioning environment and might in this way avoid repeating errors previously done.

For NDPs, the limited knowledge of the NDP site condition is caused by several factors (that are not present in construction projects), including the long-time needed for construction and operations, and the poor knowledge and information management during both construction and operations. These might have caused the loss of information about nuclear material and waste accumulated over the years, their storage locations (potentially in sections of the plants that are difficult to inspect), and their conditions (whether there have been some leakages or not), etc.

Hence, on the top of additional characterization (discussed for example by (Cross, Green, and

Adsley, 2012)), also best practices in knowledge and information management should be kept in high considerations not only during the NDP progress, but also before the beginning of the NDP, and starting from the construction of the nuclear facilities (LeClaire and LeMire, 2012). Secondly, the need for clarity regarding the waste routes and about the availability of storage and disposal facilities have also been highlighted. 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 for more 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.

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 topic 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 about what the aim is). In other words, for decommissioning, not only "how to complete 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"*.

One tentative practical guideline to address this challenge is, therefore, to carefully define waste routes and assess the availability of storage and disposal facilities before planning further work and award decommissioning contracts.

Project incentives to drive the NDPs is another topic that has been raised by the interviewees as relevant for the successful progress of the NDPs.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 (Bower *et al.*, 2002; Love *et al.*, 2010). Financial incentives are not the only researched ones: Rose & Manley (2011), for example, discuss the effectiveness of both financial incentives compared to initiatives to enhance relationships. On the topic of incentives, the experience of Rocky Flats NDP provides an interesting example. Rocky Flats was a US 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), managed by a series of weapons contractors, and during its decommissioning, its waste was shipped to other states in the US (Cameron and Lavine, 2006; DOE, 2013). 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 ten 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 the target were high, but not all the bonuses were paid immediately (Cameron & Lavine 2006; Whinch 2010). These incentive agreements were one of the drivers for the success of Rocky Flats decommissioning (Invernizzi *et al.*, 2017b).

Overall, these research findings urge project managers to focus not only on strictly technical aspects of decommissioning but also socio-economic ones, including project scoping, contracts agreements and incentivisation, as well as the development ad sharing of knowledge and expertise.

Limitations and Future Research

This research is not free of 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, which might have limited the considerations about the role played by project managers as well as his/her leadership. 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".* 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. 2017). 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 highlighted the need for inspirational leadership as relevant for the decommissioning project performance. More research on this front is, therefore, also envisaged.

Future research could also investigate each single NDP characteristic highlighted in this paper, across different industrial sectors. Also, a ranking of the importance of the project characteristics that affect the performance of decommissioning, the interconnectedness of these characteristics and their causal chain should also be investigated further, e.g. using soft system methodology (Checkland, 2000))cognitive mapping techniques (Edkins *et al.*, 2007), following (Lahdenperä, 2012; Thunberg and Fredriksson, 2018), or using Quality Comparative Analysis (QCA) (Schneider and Wagemann, 2012).

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 and Wagemann, 2012)).

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 are remarkably under-investigated. Decommissioning projects are long, complex and expensive, and there is a limited understanding of what affects their cost and time performance. Hence, there is a need to investigate these projects. The key research question is:

- *Which NDP characteristics mostly impact on the NDP performance in term of cost and time*?

To address this question, the authors examined the information collected by interviewing experienced practitioners involved in European NDPs. Caution is, however, fundamental in arriving at an overall answer to this research question, especially in studies like the present one. Indeed, from this study, a number of NDP characteristics that are thought by experienced practitioners to affect NDP performance emerged, but further studies analysing the relationship of "causation" between these NDP characteristics and the NDP performance are needed.

Reflecting on previous literature, some of these characteristics have been already highlighted as relevant for the project performance, while others have a more "unique" nature. Both deserve more in-depth research before an overarching "decommissioning theory" can be formulated.

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The authors declare that there is no conflict of interest.

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