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Original Article

Development of a multi criteria decision analysis framework for the assessment of integrated waste management options for irradiated graphite

Liam Abrahamsen-Mills [a], Alan Wareing [a], Linda Fowler [a], Richard Jarvis [a], Simon Norris [b], Anthony Banford [a, c, *]

[a] National Nuclear Laboratory, 5th Floor Chadwick House, Warrington Road, Birchwood Park, Warrington WA3 6AE, United Kingdom
[b] Radioactive Waste Management Limited, Building 329, Thomson Avenue, Harwell Campus, Didcot, Oxon, OX11 0GD, United Kingdom
[c] The Department of Chemical Engineering and Analytical Science, The Mill, The University of Manchester, Sackville Street, Manchester M13 9PL, United Kingdom

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ABSTRACT

An integrated waste management approach for irradiated graphite was developed during the European Commission project 'Treatment and Disposal of Irradiated Graphite and other Carbonaceous Waste'. This included the identification of potential options for the management of irradiated graphite, taking account of storage, retrieval, treatment and disposal methods. This paper describes how these options can be assessed using multi-criteria decision analysis (MCDA) for a case study relating to a generic power reactor. Criteria have been defined to account for safety, environmental, economic and socio-political factors, including radiological impact, resource usage, economic costs and risks. The impact of each option against each criterion has been assessed using data from the project and the wider literature. A linear additive approach has been used to convert the calculated impacts to scores. To account for the relative importance of the criteria, example weightings were allocated. This application has shown that MCDA approaches can be used to support complex decisions regarding irradiated graphite management, accounting for a wide range of criteria. Use of this approach by individual countries or organisations will need to account for the specific options, scores, weightings and constraints that apply, based on their national strategies, regulatory requirements and public acceptability.

1. Introduction

There are approximately 250,000 tonnes of irradiated graphite (i-graphite) worldwide [1–3], which originate from the use of graphite in nuclear reactors as moderator, reflector or operational material. At present, the majority of this i-graphite is held either *in-situ* within nuclear reactors or in vault/silo storage. The safe long-term management of i-graphite requires specific consideration due to its heterogeneous nature and the presence of long-lived radionuclide species such as ^{14}C and ^{36}Cl. Different approaches to the management of i-graphite have been identified and developed as part of several countries' national waste management programmes, recognising that no single waste management solution exists [3].

The European Commission project 'Treatment and Disposal of Irradiated Graphite and other Carbonaceous Waste (CARBOWASTE)' under the 7th EURATOM Framework Programme [4] sought to investigate and develop best practices in the retrieval, treatment and disposal of i-graphite. This involved bringing together the experience and knowledge from a range of organisations and stakeholders from the nuclear industry and scientific research establishments from European countries, along with international partners, to develop methods for i-graphite management [5]. As part of the project, an integrated waste management approach was developed [6–8] that was suitable for potential application by different countries and sites, each with their own particular conditions to meet (e.g. a specific disposal end point or regulatory requirements).

Wareing et al. [8] provides an overview of the characteristics of i-graphite and describes the potential techniques that could be

* Corresponding author. National Nuclear Laboratory, 5th Floor Chadwick House, Warrington Road, Birchwood Park, Warrington WA3 6AE, United Kingdom.
E-mail address: anthony.w.banford@uknnl.com (A. Banford).

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applied during the different stages of the lifecycle of i-graphite, for example, during retrieval, treatment, recycle/reuse and disposal of the graphite wastes [3,6,9–13]. Consideration of these techniques and technologies and their combinations led to the identification of a range of potential options for the management of i-graphite [8]. The purpose of this paper is to demonstrate how these options can be assessed using multi-criteria decision analysis (MCDA) to identify the most appropriate solution for a specific case study. However, it is important to note that the purpose of this example application of the approach was not to dictate a European-wide waste management strategy in relation to i-graphite. Rather, it was to demonstrate a flexible approach to assessing a particular waste management case study in a quantitative manner. Additional factors must also be taken into account, such as national strategies, regulatory approval or public acceptability.

2. The MCDA approach

There are many factors that influence the selection of the best route for each i-graphite waste stream and a method of selecting rationally between multiple options, accounting for their different strengths and weaknesses, is required. An integrated waste management approach for i-graphite enables a comprehensive analysis of the key stages from in-reactor storage through to final disposal, accounting for economic, safety, environmental and socio-political factors. MCDA provides a means of assessing this complex problem to support decision-making and can be defined as:

"… both an approach and a set of techniques, with the goal of providing an overall ordering of options, from the most preferred to the least preferred option …" [14].

A large number of MCDA tools and techniques exist, ranging from basic 'elementary' techniques through to more sophisticated and flexible methods. Different MCDA methods are based on a range of theoretical foundations [15], such as optimisation, goal aspiration, or outranking, or a combination of these. However, the different MCDA approaches all follow the same basic approach [6], although some of the steps, e.g. weighting, are not always carried out. Fig. 1 shows the major steps involved in the MCDA approach [14].

Scoring options against a number of criteria is a means of evaluating the performance of each option. Criteria against which the options are evaluated should be carefully defined, and be discriminatory between options, comprehensive, relevant, not repeated and manageable in number. Since the performance against different criteria is often measured in different units, may be non-quantitative, or otherwise difficult to compare, numerical scores are calculated to represent the performance.

Weighting of each criterion allows the decision-making team to communicate the relative importance of the criteria with respect to each other. The scoring and weighting of criteria can be performed using a mix of quantitative data and qualitative information. How these different types of quantities are compared and/or combined depends on the MCDA method chosen.

Evaluation of results may be a straightforward comparison of overall option scores; however it may also entail calculation of option scores per unit cost, or some other assessment of the results, such as a pairwise comparison between two options. Sensitivity analysis is used to establish the impact of uncertainty in scoring and so provides a method by which the significance of differences between scores can be determined.

For the CARBOWASTE project, the specific aims of the decision analysis tool were to enable:

- selection of disposal processes;
- multiple criteria comparisons of a reference case option with other options; and
- analysis of the sensitivity of the assessment findings and project decisions to changes in input data.

MCDA therefore formed an important component of the CARBOWASTE project objective for an integrated waste management approach for i-graphite. MCDA methods suitable for use in the CARBOWASTE project were identified following review of various case studies, including European Union projects [16–19].

MCDA has been increasingly applied to environmental applications with a range of MCDA techniques being applied to different application areas, including waste management [20–22]. The MCDA methods considered in the CARBOWASTE project were:

1. Multi-Attribute Utility Theory (MAUT)
2. Simple Multi-Attribute Rating Technique (SMART)
3. Analytical Hierarchy Process (AHP)
4. Outranking
5. Linear Additive
6. Ideal Point
7. Non-compensatory methods

Different techniques have different strengths and weaknesses [23–25]. These methods were assessed for the CARBOWASTE project based on criteria taken from [14]:

- internal consistency and logical soundness
- transparency
- ease of use
- data requirements not inconsistent with the importance of the issue being considered
- realistic time and manpower resource requirements for the analysis process

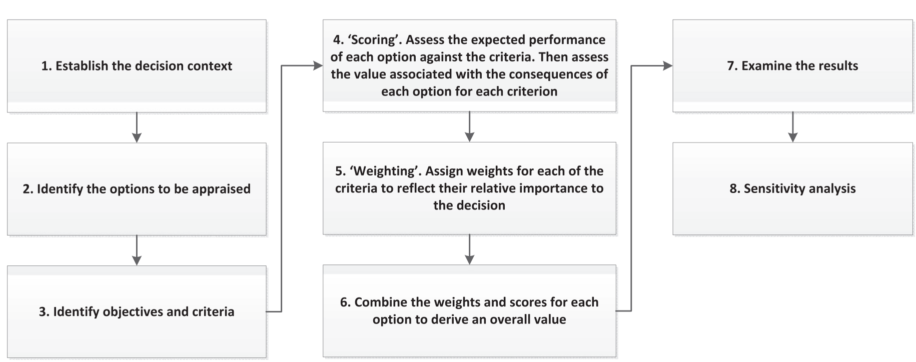

Fig. 1. Steps in the MCDA process.

- ability to provide an audit trail, and
- software availability, where needed.

From this assessment, the Ideal Point method was deselected as it is not widely used. Non-compensatory methods were identified as less suitable for the main assessment of options, although it could be useful for initial coarse screening of options. The key differentiator between the remaining methods is the level of complexity of the support software requirements, ranging from low (Linear Additive/SMART) to medium (MAUT) and high (AHP/Outranking). All of these remaining methods were considered to be suitable for deployment in the CARBOWASTE project. In practice, a simple application of the linear additive method was adopted. Reviews of the application of MCDA techniques to environmental applications have shown AHP and MAUT to be among the most referenced techniques [21,22]. Different (national) decision-makers and users may select their preferred tools according to user preference, and intended application, with ease of use expected to be a key consideration.

3. Evaluation of options and criteria

The CARBOWASTE project considered the technical and engineering design aspects of a range of waste management approaches to i-graphite. Various targets, or end points, for an integrated waste management approach were defined (such as i-graphite disposed in a repository, or recycled for further use) and the key processing stages leading to these end points were analysed [8]. Following identification of options, the next step was to identify criteria for assessing the consequences of each option.

3.1. Options and criteria

A set of 24 potential options (Table 1) that cover the range of i-graphite wastes, facilities and waste management policies relevant to different European countries was identified [8]. It is recognised that other options and permutations of options exist beyond the 24 investigated.

Prior to performing MCDA to assess the options, each should be screened based on the users' specific constraints such as appropriate national and international legislation. The national regulatory bodies in specific regions may have national positions that preclude specific options: e.g. on the basis of discharges or deferred dismantling: this would negate such options from further consideration. This screening of options was not performed in the CARBOWASTE project as this was a generic assessment involving partners from several European Union Member States, which aimed to demonstrate the MCDA technique in the generic context of i-graphite management Ultimately any approach selected for the management of i-graphite would have to meet national and regional regulatory approval.

Quantitative assessments of the 24 options were carried out in terms of the impacts of each option on a set of criteria and sub-criteria. Seven criteria were defined (Table 2), based on the three high-level objectives: environment and safety, economic and social [26]. This "triple-bottom line" approach to sustainability has influenced EU legislation [27,28] and has been used for sustainability assessment of energy systems [29,30] including nuclear energy [31] and waste disposal [32,33] as well as more broadly [34–36]. A series of audit checks against relevant international legislation, principles and guidelines [37–39] were performed to ensure that the criteria were comprehensive.

3.1.1. Environment and Public Safety

This criterion considers the potential for an option to have impacts on the environment. Since members of the public form part of this environment, impacts to them are also included here. Workers employed on the project to deliver the option are subject to additional hazards and so are considered separately in the Worker Safety criterion.

Regulated discharges to the environment are considered as part of this criterion. Releases may be radiological or non-radiological (e.g. toxic materials), or a mixture of both. Use of natural resources and impacts of operations on ecosystems are also considered here.

3.1.2. Worker safety

The Environment and Public Safety criterion considers public safety; however the workforce will be exposed to risks over and above those borne by the public since they are working on decommissioning, waste treatment and disposal sites. It is therefore important that worker safety is considered in the selection of preferred strategy options. Both radiological (dose) and non-radiological (e.g. falls, asphyxiation) impacts are considered, based on industrial worker safety statistics.

3.1.3. Security

This criterion considers the protection afforded against deliberate, malicious actions. Two aspects are identified: protection against misappropriation of materials and vulnerability of materials and buildings to malicious, purposeful attacks. The criterion also considers any safeguards necessary to support nuclear non-proliferation.

3.1.4. Economic cost

Economic factors include, at their simplest, the cost of delivering the project. This cost is assessed over all the project phases and includes the costs of research and development, design, construction, operation and decommissioning of any facility. Costs include the processing and treatment of wastes and secondary wastes formed as part of operations. Since the timescales of the entire lifecycle can be particularly prolonged (from the *in-situ* state to the disposed state), an appropriate discount rate must be selected and applied.

3.1.5. Technology predictability

Technology selection will have impacts on several criteria. Emissions and effluents will influence the Environment and Public Safety criterion, the nature of the technology (e.g. hands-on vs. remote handling) will affect the Worker Safety criterion, capital and operating costs will influence the Economic Costs criterion. Thus, most performance measures are reflected elsewhere. However, there is uncertainty associated with the feed materials and potentially equipment performance, when it is deployed, and this uncertainty results in the need for this criterion.

This criterion considers both the design uncertainty associated with novel equipment and processes, and their flexibility and robustness to variations in the feed and operating conditions. The inclusion of TRL in this criterion reflects the relative maturity of technologies under consideration; some options are mature and proven (TRL of 9) whereas others are immature requiring the development of technology, knowledge and experience.

3.1.6. Stability of employment

Nuclear power stations are often located in remote regions and are frequently a major local employer. Dramatic swings in employment can therefore have significant local impacts. Closing facilities can result in high unemployment, while construction projects can stretch the local infrastructure, making life unpleasant for local residents. Managed change in employment levels allows the community time to adjust to change. Hence, in this assessment,

Table 1
Options considered for assessment [8].

Option No.	Description
1	Encapsulation & deep repository: graphite is allowed to decay in the reactor core for 25 yr followed by remote retrieval to recover blocks of graphite for onsite encapsulation. The resulting packages are transported to a vault dedicated to graphite within a deep geological repository.
2	Size reduction of graphite for minimized waste package volume; local immobilization: Option 2 differs from Option 1 in that it performs size reduction prior to encapsulation to increase the packing of graphite into boxes.
3	Minimum processing: Option 3 differs from Option 1 in that it does not perform encapsulation of the waste, but only boxes the waste.
4	Deferred start with remote retrieval: Option 4 differs from Option 1 in that it allows an additional 50 yr for cooling in the reactor & then (in common with Option 2) performs size reduction to increase packing of graphite within boxes. This option also uses a deep geological repository where graphite wastes share a vault with other wastes.
5	Deferred start with manual retrieval: Option 5 differs from Option 4 in that it allows manually assisted retrieval to take place rather than assuming fully remote operation.
6	Minimum processing with deferred start: Option 6 differs from Option 3 in that it includes a longer *in situ* storage period & then uses manually assisted retrieval rather than fully remote retrieval.
7	Alternative retrieval & graphite form in package: Option 7 differs from Option 1 in that the graphite material is retrieved as particulate & is finally disposed of to a deep geological repository in which graphite material shares a vault with other material.
8	Alternative retrieval & repository: Option 8 differs from Option 1 in that the graphite material is retrieved underwater, & interim storage is used to provide time for the provision of an intermediate-depth waste repository.
9	Interim storage & repository: Option 9 differs from Option 1 in that interim storage is used to enable time for construction of an intermediate-depth waste repository.
10	Alternative retrieval, encapsulation and intermediate storage: Option 10 differs from Option 7 in that it allows interim storage of graphite particles prior to encapsulation, and the final destination is a surface store (which requires replacing every 150 years). Assessment is performed over a 500,000 year period.
11	*In situ* treatment & near-surface repository: Option 11 differs from Option 1 in that *in situ* heat treatment is used to condition the graphite at the end of operations. Also, a co-located near-surface repository is used in place of a dedicated deep repository.
12	*Ex situ* treatment & near surface repository: Option 12 differs from Option 1 in that *ex situ* heat treatment is used to condition the graphite to remove ^{14}C. Also, a co-located near-surface repository is used in place of a dedicated deep repository.
13	Gasification & isotopic dilution with conventional fossil fuel CO_2: Option 13 differs from Option 1 in that particulate retrieval is used to recover the graphite. Metal components are segregated from the graphite & encapsulated before the graphite is further reduced in size & gasified before isotopic dilution & release. Also, a co-located repository is used in place of a dedicated deep repository because only metal items & ash are now consigned to the repository.
14	Gasification & isotopic dilution with conventional fossil fuel CO_2 as a result of sequestration: Option 14 differs from Option 13 in that it captures the off-gas from the gasification process & sequesters it along with gases from conventional fossil fuel processes.
15	Gasification & isotopic dilution by dispersal as $^{14}CO_3$: Option 15 differs from Option 13 in that it captures the off-gas from the gasification process & discharges it to sea.
16	^{14}C reuse: Option 16 differs from Option 1 in that it selects a portion of the graphite expected to contain high levels of ^{14}C & segregates it. This graphite is roasted to produce a gaseous stream rich in tritium & ^{14}C. The remaining solid material is then routed to encapsulation & repository. The tritium & ^{14}C are then separated with the ^{14}C subjected to further enrichment before reuse. The depleted ^{12}C rich stream is discharged.
17	^{14}C reuse with no isotope separation: Option 17 differs from Option 16 in that it performs no additional 14C enrichment.
18	Graphite reuse for nuclear application only.
19	*In-situ* entombment.
20	Waste volume reduction and emission to atmosphere.
21	Make use of graphite as inert filler, removing the need for some encapsulation.
22	Immobilise in medium impermeable to ^{14}C.
23	Chemically binding ^{14}C.
24	Interim storage of raw waste followed by disposal to a repository.

Table 2
High level objectives, criteria, sub-criteria and measures used for the assessment of i-graphite management options.

Objective	Criteria	Sub-criteria	Measure (unit)
Environment and Safety	Environment and Public Safety	Radiological Impact – Human	Collective dose over 10^6 years (Man Sieverts)
		Radiological Impact – Environment	Tier 1 ERICA [40] score (–)
		Resource Usage	Energy (GJ)
		Non-radiological Discharges	Sum of dilution required to meet Environmental Quality Standard for all toxic species (m^3)
		Local Intrusion – noise	Noise (decibel.years)
		Local Intrusion – land usage	Land (hectares.years)
		Local Intrusion – transport movements	No. of truck journeys (–)
		Hazard Potential	Radiological Hazard Potential (–)
	Worker Safety	Radiological Worker Safety	Worker dose (mSv)
		Conventional Worker Safety	No. of injuries (–)
	Security	Security Misappropriation	Dose (Sv)
Economic	Economic Cost	Cost	Cost of construction/operation/decommissioning (£M)
	Technology Predictability	Concept Predictability	Technology Readiness Level of technology to be used (TRL 1 to 9) Cost to fully develop technology if not already mature (£M)
		Operational Predictability – costs as a result of risk	Potential cost to project as a result of risk (£M)
		Operational Predictability – delays as a result of risk	Potential delay to project as a result of risk (yr)
Social	Stability of Employment	Employment Level	Employment factor – Rapid Staffing Changes (jobs) (–)
	Burden on Future Generations	Burden Level	No. of decades until material no longer requires active management (–)

both dramatic increases and decreases in local employment levels are treated as a negative impact.

3.1.7. Burden on future generations

A problem with the criteria above is that continual delay might appear to be a preferred option: radioactivity decays to lower levels, costs are depreciated, and arisings of waste materials are deferred and potentially reduced. However, staff experienced in the operation of the plant retire and knowledge about the nature of the wastes is lost, buildings decay and there are moral concerns in leaving work for future generations when the benefits of the reactor operation have been experienced by the current generation. These aspects are grouped together and assessed as part of this criterion.

Another key criterion to be considered during the assessment of waste management options is that of public acceptance. The assessments carried out for CARBOWASTE did not attempt to quantify the acceptability of options to members of the public, since this is difficult to predict, and is likely to differ considerably across Member States. It is likely that impacts on certain criteria, above others, will influence the acceptability of options to members of the public. Affected communities will include those located close to reactor stations, treatment or storage facilities and the site of any waste repositories that might be constructed, as well as the population as a whole.

3.2. Data and methods

For each option, an associated option schematic was produced, giving an overview of the processes involved and considering:

- in-situ storage in the reactor;
- retrieval technique;
- treatment and conditioning of the primary and secondary wastes;
- effluent treatment (liquid and aerial);
- interim storage;
- transport of wastes and raw materials; and
- nature of the waste repository.

Not all of the steps above (such as i-graphite treatment, or disposal) are relevant for all of the options identified. Fig. 2 shows an example of an option schematic for Option 8: Alternative retrieval and repository.

The option schematic for each option was then extended to calculate the numerical performance measures that quantify the impact of the option for each of the sub-criteria. The performance measures have different units, e.g. resource use (GJ) vs. transport (number of truck journeys) (Table 2).

To calculate the performance measures, a wide range of data relating to each stage of the i-graphite lifecycle is required. For this assessment, all of the required data, including decontamination performance, costs and discharges to the environment were gathered from the open literature and CARBOWASTE partners performing supporting research. This generic assessment (and data) would require underpinning for application to a specific inventory and the specific national context. As an example, the performance measures and data requirements for the Radiological Impact Human sub-criterion are provided in Table 3.

The performance measures for each sub-criterion listed in Table 2 were determined for all 24 i-graphite treatment options. Following this, MCDA assessments could be performed.

3.3. MCDA assessments

An example of the full MCDA process was demonstrated for a case study relating to a generic power reactor (based on data for a Magnox type and scale reactor). For this case, there is a significant inventory of graphite, with high activation, and additional material (such as thermocouples) associated with the graphite.

Within the MCDA process, once all the impacts (performance measures) of each option against each criterion have been determined, a performance matrix is produced (Fig. 3). At this stage, it is possible to make comparisons between options by considering their impacts without assigning scores or weights. However, these simple methods require the sub-criteria to be considered individually when making the comparison, rather than judging overall performance.

3.3.1. Direct comparisons of performance measures (without scoring or weighting)

An initial stage of MCDA (prior to scoring and weighting) involved considering each sub-criterion in turn and examining the impact (performance measure) of each option on that sub-criterion. Fig. 4 and Fig. 5 show example MCDA outputs across the 24 options for two sub-criteria ‘Public safety: Radiological Impact - Human’ and ‘Economic Cost: Costs’. The results indicate that Option 13 (Gasification and isotopic dilution with conventional fossil fuel CO_2) results in the greatest radiological impact (1.69×10^5 Man Sv), whilst Option 1 (Encapsulation and disposal in deep repository) results in the lowest radiological impact (0.01 Man Sv) due to the effectiveness of a repository in isolating the waste and minimising discharges. In terms of economic costs, Option 10 (Alternative retrieval, encapsulation and intermediate storage) has the highest total cost (£86.9 billion) due to its requirement to rebuild a surface store every 150 years for 500,000 years and Option 19 (In-situ entombment) the lowest (£55.93 million).

These results allow a detailed examination of the impact of each option on each of the sub-criteria. Since the sub-criteria consider a range of unequal measures, with different units, the direct comparison of performance between options is not possible at this stage. A second stage of the MCDA process was therefore undertaken to identify leading options.

4. Identification of leading options

Following the initial assessment of the MCDA process, a scoring and weighting process was undertaken to test whether the process allowed the overall best and worst-performing options for the management of i-graphite to be identified from the 24 options considered. A workshop was held to seek the views of key stakeholders in the management, treatment and disposal of i-graphite.

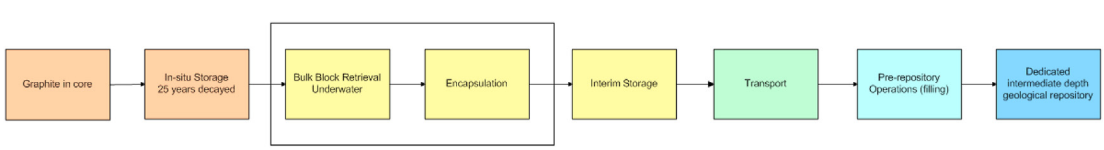

Fig. 2. Option schematic for Option 8: Alternative retrieval and repository.

Table 3
Performance measures and data requirements for Radiological Impact - Human sub-criterion.

Sub-Criteria	Measure	Measure Units	Data Requirement	Data Units
Radiological Impact – Human	Collective Dose over 10^6 years	Man Sieverts	Time Varying Discharge Profile Aerial and Liquid Collective Dose Factors for each site	End of pipe TBq vs. time Man Sieverts/TBq

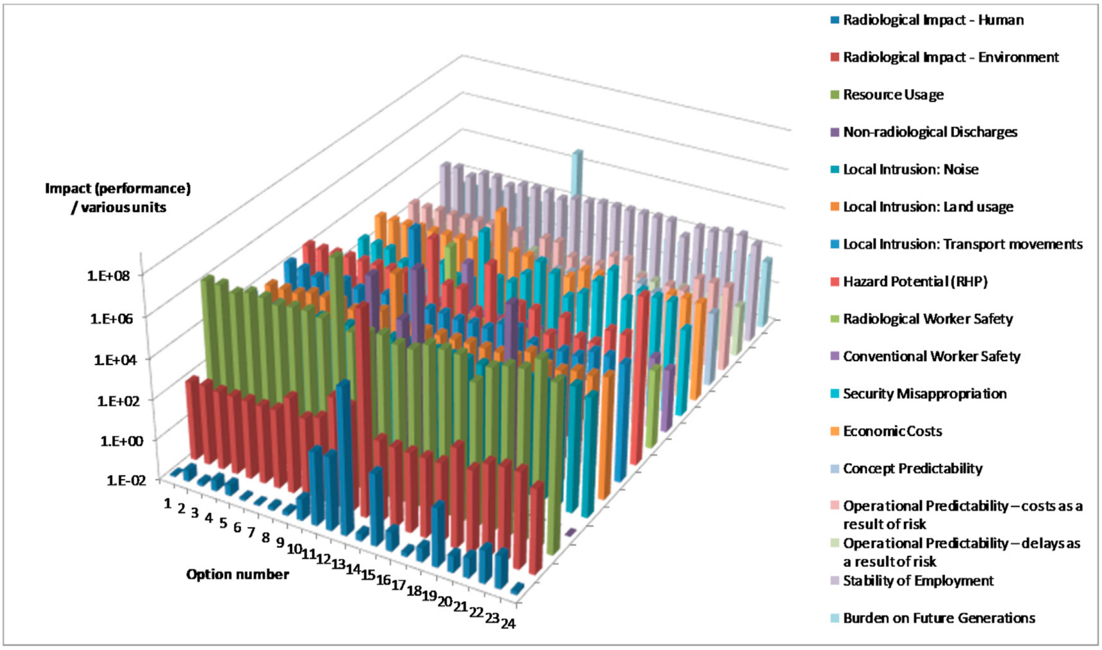

Fig. 3. Performance matrix for all options against all criteria.

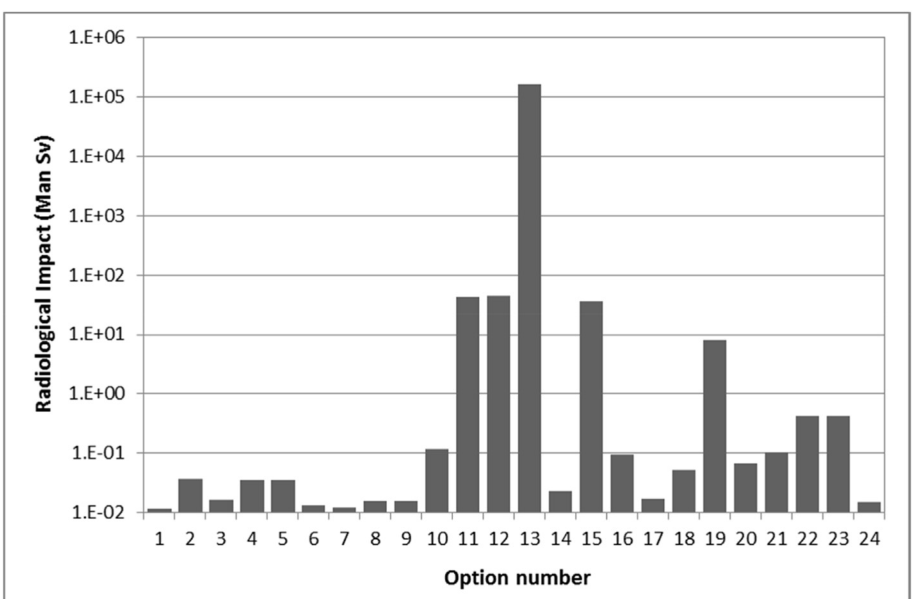

Fig. 4. Public Safety: Radiological Impact – Human, measured across all options (note the logarithmic scale on the y-axis).

The attendees were drawn from the CARBOWASTE consortium members and included representatives from waste management organisations, research organisations and stakeholders from across Europe. Through discussions and debate, attendees agreed on a generic MCDA approach and a series of weightings to indicate the relative importance of each assessment sub-criterion. These were adopted to test the methodology, which followed the approach shown in Fig. 1 using a linear additive MCDA method [14]. A number of different approaches and combinations of weightings were trialled in order to determine a suitable approach that

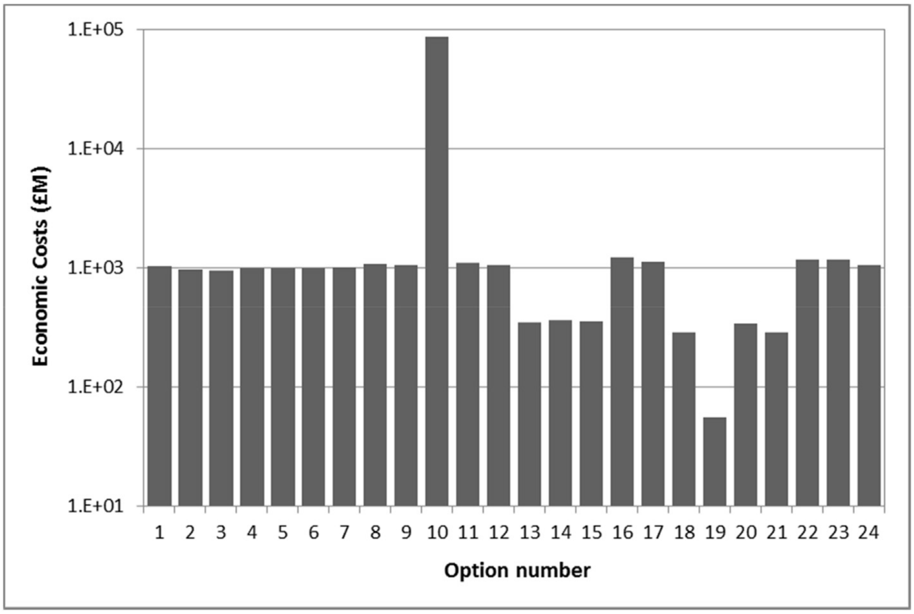

Fig. 5. Economic costs measured across all options (note the logarithmic scale on the y-axis).

individual Member States could utilise for their own i-graphite management. It would be expected that a broader range of stakeholders would be involved when the MCDA was applied by each Member State, and that the stakeholders could differ between Member States.

In the scoring of the sub-criteria, the minimum and maximum values calculated for a sub-criterion across all options were considered and assigned a score of 0 for the lowest value and a score of 100 for the highest value. Intermediate values were given a score between 0 and 100 based on their relative position within the minimum and maximum values on a linear scale. This approach utilised a local scoring model (where low and high performance limits are derived from the scope of the current problems for which a range of options are being considered) with no judgement in the scoring process (as scores are applied automatically). This converted the performance matrix (Fig. 3) into a scores matrix (Fig. 6).

Applying the linear additive approach for scoring was found to have some disadvantages, e.g. for some of the radioactive discharges data, a value several orders of magnitude above a range of smaller values for other options skews the scores so that the option with the large discharges receives a score of 0, while all the other options receive a score of 100, ignoring the differences between them. This is illustrated in Fig. 7 which indicates the linear scale applied for the scoring of options against the 'Radiological Impact – Human' sub-criterion. Since Option 13 is predicted to have an impact several orders of magnitude greater than any other option (Fig. 4), this option receives a score of 0, and all other options a score of 100, even though there are highly significant differences in the predicted impacts between these options on this sub-criterion. This issue was dealt with by eliminating the worst-scoring options iteratively, redefining the local minimum and maximum impacts, and hence the range of scores, each time until options could be differentiated.

To allow the prioritisation of sub-criteria, weightings were applied to each. The MCDA workshop attendees proposed several different weighting allocations in order to explore the sensitivity of the process to a range of criteria prioritisations.

Three of the example allocations of weightings (Allocations A, B and C) arising from the workshop are presented in Table 4 to demonstrate the process and do not reflect any individual organisation's view. Each sub-criterion is judged to have high, medium or low importance. In order to quantify their relative importance, these 'weighting bands' are then assigned a numerical representor. Two different approaches were trialled in quantifying the weightings: extreme and narrow. In the extreme weighting approach, high priority = 100, medium priority = 50, low priority = 1. This approach results in the highly weighted sub-criterion to be 100 times more important in determining the overall weighted scores than the low weighted sub-criterion. In the narrow range of weightings (high = 75, medium = 50, low = 25), the high weighted sub-criterion has three times more impact than the low weighted sub-criterion.

For each sub-criterion, the score was multiplied by the weighting to give a weighted score. These weighted scores were summed and an overall weighted score for that option determined, i.e. the linear additive approach. A consistent approach to scoring and weighting must be applied to all options being considered, i.e. it is not possible to use one method of scoring and/or weighting for one option and an alternative method for others.

Fig. 8 displays the overall weighted scores for all of the twenty four options considered. The best-scoring option is labelled green and the worst-scoring option labelled red. Following the initial assessment of all 24 options, the worst-scoring option was removed, and the scores of the remaining 23 options were re-normalised and re-allocated overall weighted scores. This process was then repeated, with the successive removal of the worst-scoring option each time (see, for example, Fig. 9 with only four remaining options). This enables the user to gradually focus on a successively smaller number of the best-scoring options and obtain a greater resolution/discretisation of scores for those remaining options. Fig. 8A–C give results for allocations A-C respectively. Fig. 8D displays the results of the narrow weightings for allocation A and can be compared to the results of the extreme weightings used in Fig. 8A.

5. Discussion

I-graphite management options that have significant radiological discharges (e.g. Options 13 and 15) perform poorly on

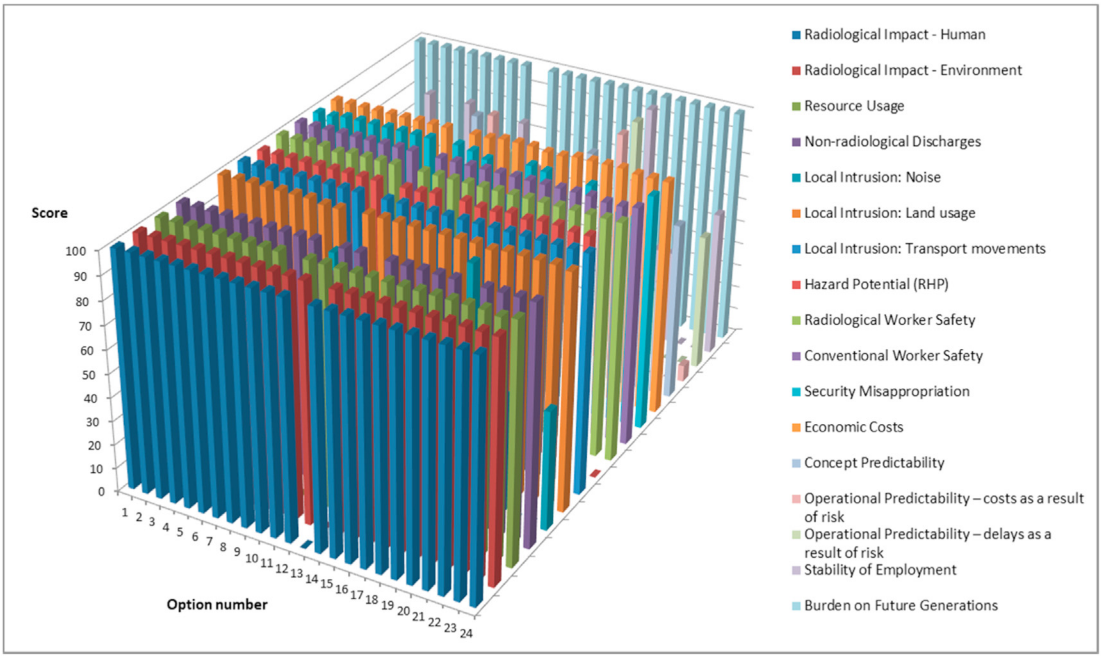

Fig. 6. Performance matrix for all options against all criteria, impacts converted to scores.

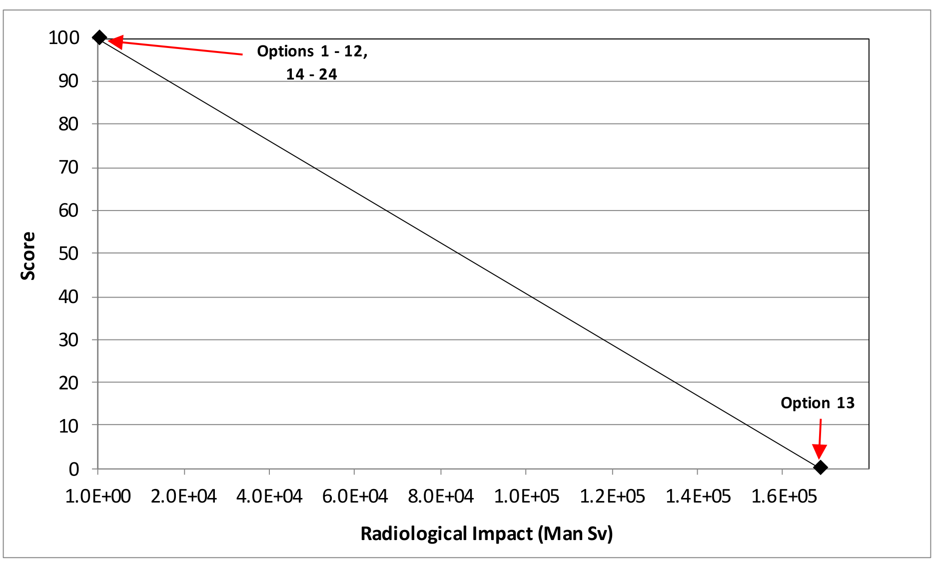

Fig. 7. Local scoring approach using a linear relationship between score and impact, shown for 'Radiological Impact - Human' sub-criterion and all 24 options.

environmental criteria, but these options generally benefit from reduced hazards, resource use and transport requirements, and may be cheaper than other options. Due to the environmental impacts, these options may only be appropriate in certain circumstances.

Options that include the use of a deep geological repository (1–7) perform moderately well in this assessment due to the reduced radiological discharges, hazard potential and security impacts balanced against the negative impacts of repository construction (costs, resource usage etc.). The most costly options are those which consider large, repeated construction activities, such as those requiring many treatment facilities or indefinite storage, such as Option 10, which considers storage for 500,000 years.

Options that avoid the use of a deep geological repository performed well in this assessment due to the avoidance of the significant resource usage and economic costs associated with repository construction. The scaled allocation of these impacts to i-graphite needs to be considered alongside national strategies. For example, if a deep geological repository were to be constructed solely for the disposal of i-graphite, the complete allocation of the repository's impacts to i-graphite could make such options unviable. If, however, a geological repository for other wastes, e.g. spent fuel or high level waste were already planned, or in existence, the additional inclusion of i-graphite would have much less impact.

Continued above ground storage for a very long time period (500,000 years considered in Option 10) is not a favourable option for most criteria. In particular, it is expensive, uses extensive land, resources and transport, imposes the largest burden on future

Table 4
Example sub-criteria weightings proposed during MCDA Workshop. These priorities are for illustrative purposes and do not reflect any individual organisation's view.

Sub-criteria	Allocation A Weighting Band	Allocation B Weighting Band	Allocation C Weighting Band	Allocation A Extreme Weightings	Allocation A Narrow Weightings
Radiological impact - human	High	High	High	100	75
Radiological impact –environment	High	High	High	100	75
Resource usage	High	Low	High	100	75
Non-radiological discharges	Medium	Medium	Low	50	50
Local intrusion: noise	Low	Low	Low	1	25
Local intrusion: land use	Low	Low	Low	1	25
Local intrusion: truck journeys	Medium	Low	Low	50	50
Hazard potential	Medium	High	High	50	50
Radiological worker safety	High	High	Low	100	75
Conventional worker safety	High	High	Low	100	75
Security misappropriation	Medium	High	Low	50	50
Economic cost	Medium	Low	High	50	50
Concept predictability	Low	Low	High	1	25
Operational predictability	Low	Low	High	1	25
Employment level	Low	Low	High	1	25
Burden on future generations	Low	High	Medium	1	25

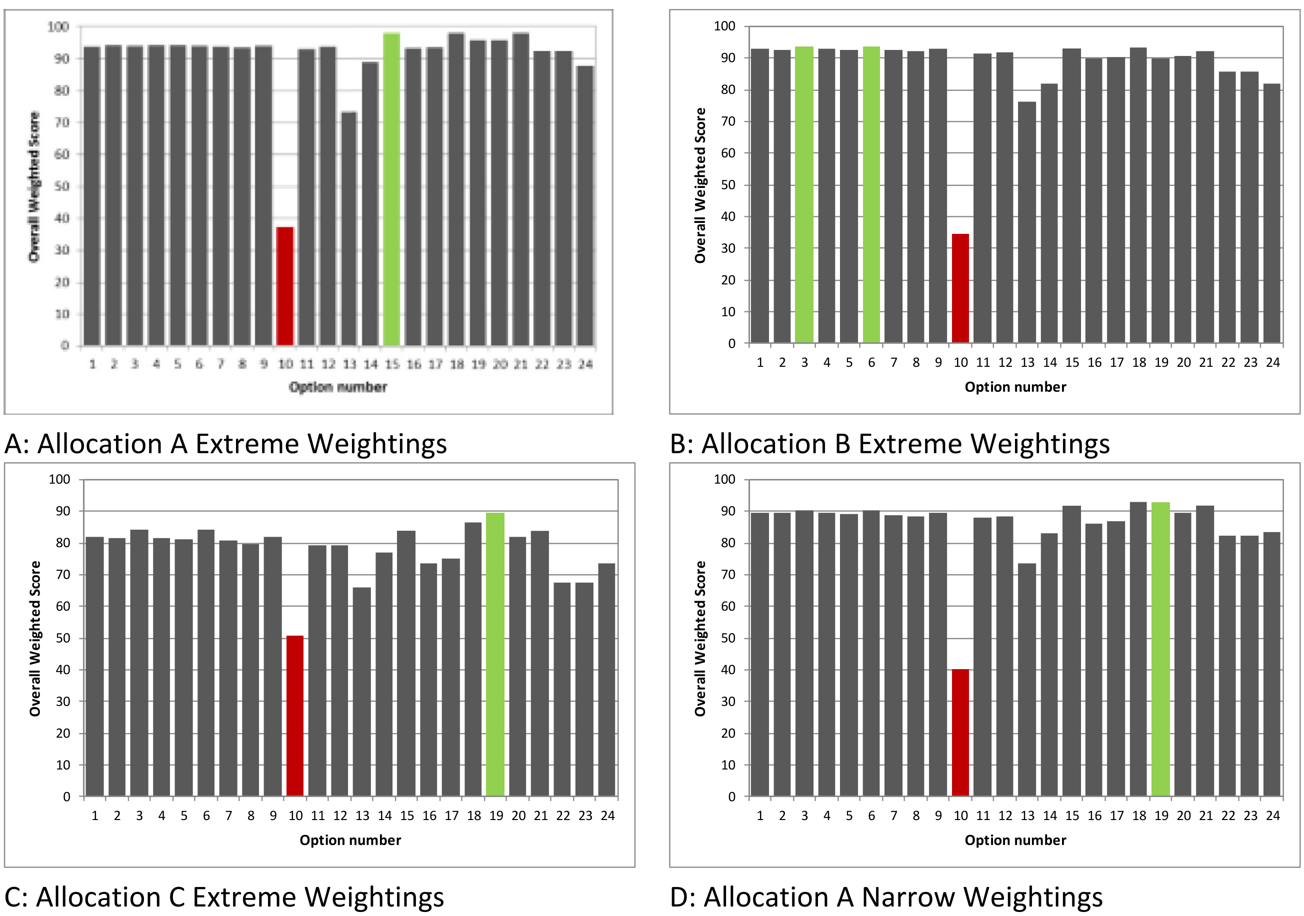

Fig. 8. Overall weighted scores for all 24 options for extreme weightings using (A) allocation A, (B) allocation B and (C) allocation C and for (D) narrow weightings using allocation A.

generations, has the potential for injuries due to the need for multiple construction works over time and has the poorest security. Reduced operational risk is the key advantage due to the wide international track record of constructing above ground stores.

When assessing all 24 options using the scores and example weightings presented here, Option 15 (gasification & isotopic dilution by dispersal as carbonate) initially performed the best and Option 10 (alternative retrieval, encapsulation and indefinite storage) performed the worst for the power reactor case study. Upon removing some of the worst-performing options from the assessment and focussing on a smaller number of options, Option 19 (in-situ entombment) emerged as the best option.

Option 15 reacts the graphite before capturing it as a carbonate which is then combined with other carbonate derived from non-nuclear sources (this could include carbon captured from conventional power stations for example). The resulting stream is discharged to sea. This has the effect of diluting the ^{14}C and so resulting in less localised, but more widespread impacts. The option

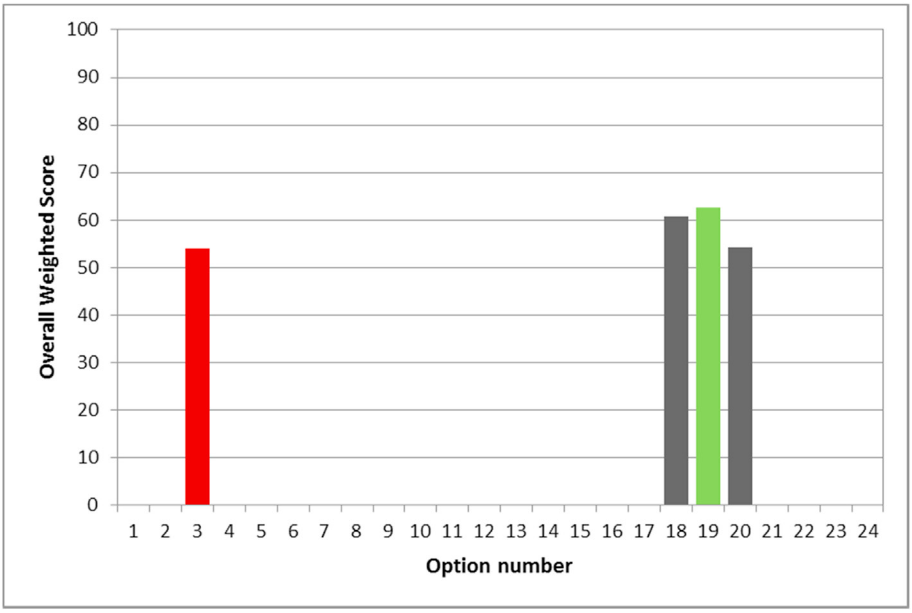

Fig. 9. Overall weighted scores for remaining four options based on 'Allocation A – Extreme Weightings'.

performed poorly for radiological impact (human), but well for impact on the environment (which is based on concentration of discharges), security (since the stream was dispersed, and so was not vulnerable to malicious action) and resource use (no encapsulants were required).

Whilst there is some experience regarding entombment, or *in-situ* decommissioning, of legacy nuclear facilities in the United States and Russia [41], and as a temporary solution for acutely damaged reactors, the approach of long-term entombment has not been extensively applied in practice to graphite-moderated power reactors. As such, it would likely require significant technological development before a safety case could be demonstrated for its use in immobilising i-graphite *in-situ* and the approach may not be acceptable to Member States. In assessing this option, it has been assumed that entombment can be performed in such a way that no ongoing maintenance of the entombed waste is required, although long term monitoring is likely to be expected. Contrasting this as the best option, with option 10 (indefinite surface storage, with stores replaced every 150 years), shows that the potential impact of developing very long lived stores and/or waste packages is significant.

Importantly, and perhaps unexpectedly, when successively removing the worst performing options from the assessment, it is possible for the best overall option determined by MCDA to change. This is due to better differentiation of the options through reassignment of scores. Depending on the criteria weights used this can result in changes of ranking among options. For example, a variant case for Option 19, which considered a monitoring and maintenance period of 1,000 years, was the best-scoring option in the first stage of assessment but, as the worst-scoring options were successively removed, its relative performance fell and it emerged as the worst-performing option part way through the process.

Several sensitivity cases were also examined to determine the effects of various normalised scoring and weighting configurations. These used different weighting allocations (Allocation B and Allocation C presented in Table 4) to investigate the impacts of prioritising the sub-criteria differently to that decided upon in the MCDA workshop. This is because the relative perspectives of scientists and engineers involved in the industry could be different from those of governments, regulators or members of the public, for example. In choosing alternative weighting allocations, an attempt was made to explore the effects of considering the priorities of two different, hypothetical, stakeholders. Narrow weighting bands (75/50/25) were considered for these alternative weighting allocations. The sensitivity analysis using the alternative weighting systems showed that, for the 24 options considered, the different weighting allocations had little effect in determining the relative rankings (i.e. the results showed low sensitivity to the weighting allocations). Consistently, Option 10 (Alternative retrieval, encapsulation and indefinite storage) was the worst-performing option and options 13 and 14 (variants of Gasification & isotopic dilution) also performed poorly in all cases. Four of the top 6 best performing options were common across all 3 allocations:

- Option 3 (Minimum processing to Deep Repository)
- Option 18 (Graphite reuse for nuclear application)
- Option 19 (*In-situ* entombment)
- Option 20 (Waste volume reduction and emission to atmosphere)

The use of the narrow and extreme weightings can be compared using Fig. 8a and d. For both weightings Options 10 (Particulate Retrieval, encapsulation and intermediate storage) and 13 (Gasification & isotopic dilution) performed poorly while options 3 (Minimum processing), 18 (Graphite reuse for nuclear application), 19 (In-situ entombment), 20 (Waste volume reduction and emission to atmosphere) and 21 (Use graphite as inert filler) were the best performing options, though the ordering varied between the different weightings.

The results show that MCDA techniques can assist in identifying high-performing and low-performing options. The selection of the absolute best result will not always be possible both because the MCDA has to be placed into the wider framework of national policy and because sensitivity assessment is likely to identify a range of credible options [20]. For the handling of i-graphite using the weightings established in this paper, options 3 (Minimum processing), 18 (Graphite reuse for nuclear application), 19 (In-situ entombment) and 20 (Waste volume reduction and emission to atmosphere) appeared at the top of each set of weightings and so should be further considered.

6. Conclusions

MCDA tools can assist in the making of complex decisions that must account for a wide range of diverse criteria. Here, it has been shown that a linear additive approach can assist in determining a waste management approach to i-graphite. First, a comprehensive set of twenty four options were identified, spanning in-reactor storage, retrieval, processing, treatment, recycling, and disposal. Next, a series of criteria and sub-criteria were identified in order to evaluate the impacts and consequences of each option. A detailed evaluation of each option against the criteria was performed, utilising data from the CARBOWASTE project and the wider literature. This included the predicted radioactive discharges, resource usage, economic costs and risks, amongst others, over the option lifetime. These impacts, or performance measures (Table S1 and Table S2 in supplementary data), against each criterion are diverse in nature and difficult to compare in order to select preferred options. To account for this, the impacts are converted into scores based on a local, linear approach, in which the best performing option receives the highest score (100) for that criterion, and the worst performing option receives the lowest score (0). Intermediate performing options receive a scaled score based on their relative position between the best and worst. In cases where the impacts for one criterion vary greatly over many orders of magnitude, this linear allocation of scores can be problematic, since a particularly poor performing option can receive a score of 0 and all other options receive a score of 100, masking their differences and producing misleading results.

This scoring allocation problem can be overcome by utilising alternative scoring approaches, or by successively removing the worst performing options in order to focus more closely on the remaining options. This process can result in the best overall option to change as the local scoring maxima and minima are re-baselined.

The allocation of scores is primarily an automated process, and does not generally involve judgement. In order for certain criteria to be prioritised, they are assigned weightings, which are multiplied by the calculated scores to give weighted scores. These are then used to determine the overall best performing options. Sensitivity analysis allows the user to determine the importance of different scores and weighting scenarios.

The example MCDA results shown here provide a number of possible outcomes of analyses. However, it is not possible to state here which i-graphite management option is best for any individual national programme. The tools and processes developed in the CARBOWASTE project can be used by individual countries or organisations to determine their own best option(s), by applying their own scores, weightings and constraints. The use of this MCDA assessment tool provides supporting arguments in a wider process for the identification of preferred options for the management of i-graphite that will need to take into account many more factors that cannot be represented quantitatively, such as national strategies, regulatory approval and public acceptability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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