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Identification of Preferred Options

Author(s): **Liam Abrahamsen, Alan Wareing (NNL)**

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Executive summary

The objective for Work Package 1 of the CARBOWASTE project was to establish an integrated waste management approach for i-graphite waste, which would:

- address the complete life cycle: in reactor storage, conditioning, retrieval and treatment to final disposal;
- provide a “cradle to grave” approach from in-situ graphite to final solution; and
- provide a “toolbox” approach capable of application to different situations and member states.

Through ongoing interaction with CARBOWASTE Work Packages 2 to 6, consensus was achieved on twenty four potential options for the management of i-graphite. Multi Criteria Decision Analysis (MCDA) assessments have been undertaken to determine best and worst-scoring options, and a number of sensitivity cases have also been examined to determine the effects of various normalised scoring and weighting configurations.

The purpose of the MCDA assessment presented here and in Wareing *et al.* (2013) is to identify and test a process than can be utilised by the CARBOWASTE partner countries. It is not possible to select a preferred option for all countries, since each will have its own specific national strategies, constraints and regulations that will preclude certain options from being viable.

When assessing all twenty four options considered by the CARBOWASTE project (and not removing any based on constraints), Option 19 (in-situ entombment) performs best and Option 10 (indefinite storage) performs worst for Case Study 1 (power reactor). The entombment concept, however, may not be technically achievable.

Options that avoid the use of a deep geological repository perform 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 member states’ national strategies, however. Options that include the use of a deep geological repository perform moderately well in this assessment due to the improved radiological discharges, hazard potential and security impacts balanced against the negative impacts of repository construction. The worst scoring options are those which consider large, repeated construction activities, such as many treatment facilities or indefinite storage.

Different weighting systems have been applied to examine the effects of varying the impact of each criterion in determining the overall weighted score. It was found that, for the twenty four options considered, the different weighting allocations had little effect in determining the relative rankings.

A qualitative assessment has been undertaken for Case Studies 2 and 3 (i-graphite in a vault/silo, and a research reactor). Each of the twenty four options was examined to identify particular stages that could not be applied, or would require significant modification to apply, to Case Study 2 or Case Study 3. It was noted that, other than the early process stages in all options not being applicable to graphite in a vault, the majority of options remain appropriate for each of the three Case Studies, although specific practicalities for application may vary slightly.

Revisions						
Rev.	Date	Short description	Author	Internal Review	Task Leader	WP Leader
01	28/03/2013	1st issue	Abrahamsen, L Wareing, A NNL	Holmes, C NNL Approver: Wood, M NNL	Banford, A NNL	Banford, A NNL

List of Acronyms

AGR	Advanced Gas-cooled Reactor
ALARP	As Low as Reasonably Practicable
ANDRA	Agence Nationale pour la Gestion des Déchets Radioactifs
AVR	Arbeitsgemeinschaft Versuchsreaktor (test pebble bed reactor)
BAT	Best Available Technique
CCS	Carbon Capture and Storage
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
EA	Environmental Agency
EDF	Électricité de France
ENRESA	Empresa Nacional de Residuos Radiactivos
FZJ	Forschungszentrum Jülich
GDF	Geological Disposal Facility
GLEEP	Graphite Low Energy Experimental Pile
HSE	Health and Safety Executive
IAEA	International Atomic Energy Agency
ILW	Intermediate Level Waste
MAUT	Multi Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
MTR	Materials Test Reactor
NDA	Nuclear Decommissioning Authority
NECSA	South African Nuclear Energy Corporation
NNL	National Nuclear Laboratory
PGA	Pile Grade A (a grade of graphite)
PSA	Pressure Swing Absorption
R&D	Research & Development
RWMD	(NDA) Radioactive Waste Management Directorate
TRL	Technology Readiness Level
SHS	Self-propagating High temperature Synthesis
SMART	Simple Multi Attribute Rating Technique
UNGG	Uranium Naturel Graphite Gaz Reactor
WAGR	Windscale Advanced Gas Reactor

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1 Introduction

The objective for Work Package 1 of the CARBOWASTE project was to establish an integrated waste management approach for i-graphite waste, which would:

- address the complete life cycle: in reactor storage, conditioning, retrieval and treatment to final disposal;
- provide a “cradle to grave” approach from in-situ graphite to final solution; and
- provide a “toolbox” approach capable of application to different situations and member states.

In order to achieve this, Work Package 1 (WP1) participants sought to understand the current challenges in the management of i-graphite through a review of existing knowledge. Following this, key endpoints were identified and a roadmap was developed to determine how these might be attained.

Through ongoing interaction with CARBOWASTE Work Packages 2 to 6, consensus was achieved on twenty four potential options for the management of i-graphite, which have subsequently been analysed using Multi-Criteria Decision Analysis (MCDA) techniques. Table 1 provides a list of the twenty four options considered. Further detail for these options is provided in the MCDA Assessments report (Wareing *et al.,* 2013).

This report presents the results of the analysis of preferred options for the management of i-graphite. However, the analysis presented here should not be used in isolation to draw a conclusion as to which option is best for any individual member state. Individual member states can use the tools and processes presented to determine their own best option by applying their own scores, weightings and constraints.

The 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 context many more factors that cannot be represented quantitatively. For example, the national strategy for the management of waste will need to be considered. This means that some options may not be acceptable at all, and potentially a single option may need to be applied to the graphite from all of a nation’s reactors rather than a separate option chosen for each reactor. Some partner countries have only one reactor whilst others have many. If there is only a single reactor then many more options for the treatment of i-graphite may be available. Conversely, having a large number of reactors may close down some options. For example, the case could be made for the entombment of a single reactor but may be hard to justify for tens of reactors. Economies of scale also need to be taken into account. Constructing a facility to treat graphite from one reactor may be economically unviable, but using the same facility to treat graphite from many reactors may be viable.

Table 1 List of twenty four options considered for assessment

Option Number	Description
1	Encapsulation and deep repository
2	Size reduce graphite for minimised waste package volume; local immobilisation
3	Minimum processing
4	Deferred start with remote retrieval
5	Deferred start with manual retrieval
6	Minimum processing with deferred start
7	Alternative retrieval and graphite form in package
8	Alternative retrieval and repository
9	Interim storage and repository
10	Alternative retrieval, encapsulation and intermediate storage
11	In-situ treatment and near-surface repository
12	Ex-situ treatment and near surface repository
13	Gasification and isotopic dilution with conventional fossil fuel CO_2
14	Gasification and isotopic dilution with conventional fossil fuel CO_2 as a result of sequestration
15	Gasification and isotopic dilution by dispersal as CO_3 in the sea
16	^{14}C re-use
17	^{14}C re-use with no isotope separation
18	Graphite re-use 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 bind ^{14}C
24	Interim storage of raw waste and repository

2 MCDA Method

2.1 Background

A form of the linear additive model was selected for CARBOWASTE MCDA assessment. The method can be distilled down to the following essential steps:

- Decide on the scoring system and scale (typically between 0 and 100); typically higher scores reflect better performance.
- Determine weighting factors (e.g. between 1 and 100), and ascribe weightings to each criterion.
- Determine the levels of performance for the two reference points (0 and 100). In a global scale model the scores of 0 and 100 are associated with the worst and best performances that could be encountered in any circumstances, whereas in a local scoring model the low and high performance limit are derived from the scope of the current problems for which a range of options are being considered. Global scaling allows for the ready introduction of new options but it can be difficult to define the absolute performance limits for a number of criteria.
- For each option, allot a scoring value against the criterion.
- In the linear approach, the option's score against each criterion is multiplied by the weighting attributed to that criterion and then the weighted scores are added together to derive an overall score for the option.

For the model to provide reliable outputs with the simple additive approach, criteria need to be independent of each other. Uncertainty assessment is not formally built into the approach, but can be introduced through a second stage of sensitivity analysis.

2.2 Workshop

The WP1 MCDA workshop (Abrahamsen, 2013) took place over three days, 9^{th} to 11^{th} January 2013, with the following objectives:

- demonstrate the MCDA tool developed by NNL for the selection of preferred options for i-graphite;
- explore the different user options for scoring and weighting against previously agreed criteria; and
- discuss country-specific constraints and methods of incorporating them into the MCDA process.

The linear additive MCDA process utilised during the workshop considered the minimum and maximum values calculated for a sub-criterion across all options and assigned a score of 1 for the lowest value and a score of 100 for the highest value. Intermediate values were given a score between 1 and 100 based on their relative position within the minimum and maximum values on a linear scale. This approach uses no judgement in the scoring process (as scores are applied automatically), although judgement is provided in determining the weightings.

It was noted that this linear additive approach has its downsides, 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 1, while all the other options receive a score of 100, ignoring the differences between them. This was addressed by removing outlying options and rescoring if necessary.

Weightings are applied to each sub-criterion to allow prioritisation of certain sub-criteria over others. For each sub-criterion, the score is multiplied by the weighting to give a weighted score. These weighted scores are summed and an overall weighted score for that option is determined. For an MCDA assessment, 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.

3 Results

During the MCDA workshop an allocation of weightings to each criterion was decided upon. Initially, these bands corresponded to extreme numerical weightings (high = 100, medium = 50, low = 1). This is referred to as 'Allocation A – Extreme Weightings', and is shown in Table 2.

As part of the sensitivity study (see later section), a narrower range of weightings is used (high = 75, medium = 50, low = 25), based on the same allocation of high / medium / low to each criterion decided upon in the workshop. This is referred to as 'Allocation A – Narrow Weightings' and explores the effects of a less extreme method of weighting than that described above. When using extreme weightings, high vs. low equates to 100 vs. 1, causing the high weighted criterion to be 100 times more important in the determining of overall weighted scores than the low weighted criterion. When using narrow weightings, this effect is reduced: high vs. low equates to 75 vs. 25, with the high weighted criterion having three times more impact than the low weighted criterion.

Table 2 Criteria weightings decided upon during the MCDA Workshop (Allocation A)

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

Later in the sensitivity analysis section, different weighting allocations (alternatives to those presented in Table 2) are explored. This is to investigate the impacts of prioritising the criteria differently to that decided upon in the MCDA workshop, since this is only one of any number of users' options for weighting.

It was noted during the MCDA workshop that it is difficult for CARBOWASTE partners to assign a definitive set of weightings, since the priorities of scientists and engineers are likely to be different to those of governments, regulators or members of the public, for example. In choosing alternative weighting allocations, an attempt is made to explore the effects of considering the priorities of two different, hypothetical, stakeholders. Hypothetical stakeholder 1 places a high priority on radiological impacts due to discharges, worker safety, hazard potential, security misappropriation and burden on future generations. Hypothetical stakeholder 2 places a high priority on radiological impacts due to discharges, resource usage, hazard potential, economic costs, and concept and operational predictability.

These are represented by 'Allocation B – Narrow Weightings' and 'Allocation C – Narrow Weightings', the details of which are provided in Table 3 and Table 4 respectively. For simplicity, only narrow weighting bands (75 / 50 / 25) are considered for these alternative weighting allocations.

Table 3 Criteria weightings representing hypothetical stakeholder 1 (Allocation B)

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

Table 4 Criteria weightings representing hypothetical stakeholder 2 (Allocation C)

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

The following figures display the overall weighted scores for all options being considered in a particular stage of the MCDA assessment. The best-scoring option is labelled green and the worst-scoring option labelled red. Initially, all twenty four options are assessed together.

By applying the process developed during the MCDA workshop, the worst-scoring option is removed, and the scores of the remaining twenty three options are re-normalised and are reallocated overall weighted scores.

This process is repeated, with the successive removal of the worst-scoring option each time. 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. At each stage, a smaller number of remaining options are compared.

Throughout this process, poorly scoring options are removed and the identification of a number of preferred options (based on the particular weightings chosen) is possible.

For a discussion of why certain options perform well in certain criteria, refer to the MCDA Assessments report (Wareing *et al.,* 2013).

It should be noted that options that have been deemed unacceptable in a particular partner country should be removed (via constraints) prior to MCDA assessment. As such, it is unlikely that in reality any user would consider as many as twenty four options via the MCDA process described. Options that score well in this assessment of all twenty four CARBOWASTE options may not be acceptable to all (or any) partner countries; they have been determined in order to provide a fully representative set of options. Each partner country must make its own assessment as to the acceptability of any particular option.

Figure 1 to Figure 4 show the overall weighted scores for 'Allocation A – Extreme Weightings' at various stages of the MCDA process. The intermediate results are presented in full in Appendix 1.

Figure 1 shows the overall weighted scores for all twenty four options, based on 'Extreme Weightings – Allocation A'.

Apart from Option 10 and Option 13, all the options have a similar score. Option 15 (Gasification and isotopic dilution by dispersal as CO_3 in the sea) is the best-scoring option and Option 10 (Alternative retrieval, encapsulation and indefinite storage) is the worst-scoring option.

Option 10 scores badly due to being the worst-performing option in resource usage, land use, truck journeys, hazard potential, worker radiological safety, worker conventional safety, security misappropriation, economic costs and burden on future generations, due to the impacts of continually replacing surface stores. See Figure 27 in Wareing *et al.* (2013) for a pairwise comparison between Option 10 and Option 1, which displays the greater impacts of the former option in many of the criteria.

Option 15 is among the options with the highest doses to public due to discharges (see Figure 2 in Wareing *et al.,* 2013). Whilst doses to the public are calculated based on the total activity released, environmental impacts are based on the activity concentration of discharges. It is assumed that ^{14}C discharged to sea is diluted to such an extent that the impact on the environmental safety criterion is negligible.

Despite its large doses to public due to discharges, Option 15 is among the best performing options in many of the other criteria and at this initial stage of MCDA assessment it is the best performing option under this weighting allocation.

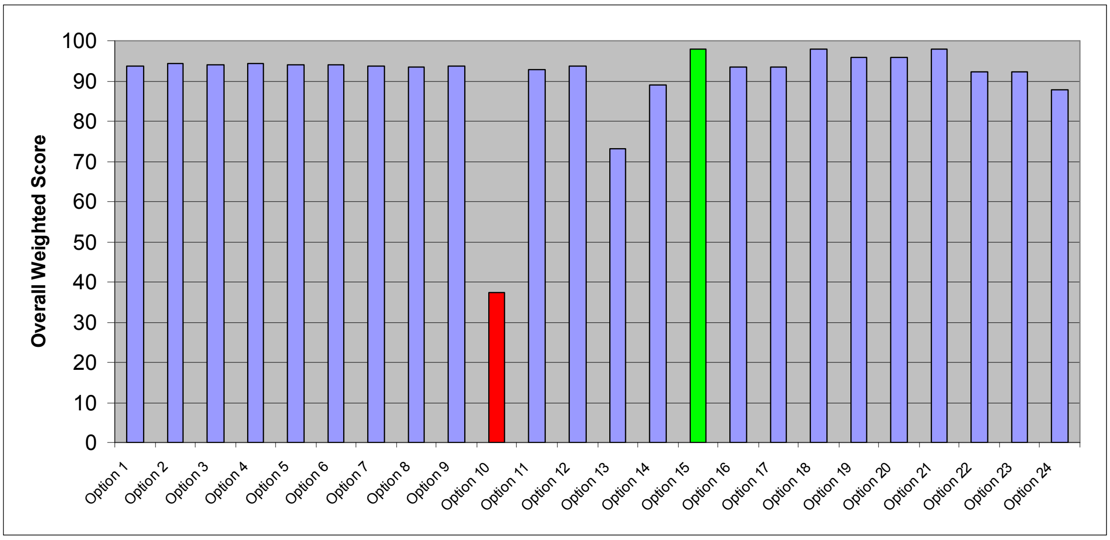


Figure 1 Overall weighted scores for all twenty four options based on 'Allocation A – Extreme Weightings'

Figure 2 shows the re-normalised results following the removal of Option 10 from the assessment. The remaining options display a greater range of overall weighted scores; note the expanded y-axis.

Option 19 (In-situ entombment) is now the best-scoring option and Option 23 (Chemically bind ^{14}C) the worst. It is somewhat surprising that the option which scores the best can change upon removing the worst-scoring option from the assessment. This is due to the allocation of weighted scores that are based on the outputs from all the options in the current assessment. The removal of a poorly scoring option can cause the performance of a well scoring option to shift in certain criteria, since performance is assessed relatively, based on a linear scale between the best and worst-scoring options in that criterion.

Option 23 scores badly due to its doses to public due to discharges, resource usage, noise, cost of delay as a result of risk, stability of employment, in all of which it is among the worst-performing options (see Figure 40 in Wareing *et al.* (2013)). This option is based on a chemical binding process similar to the Russian Self-propagating High-temperature Synthesis (SHS) method.

Option 19 scores well, partly due to it having no repository. It has a low impact on resource use, truck journeys, worker safety (it involves a low number of workers), economic costs, technical risk, changes in employment, and a low burden on future generations. This option has a far greater dose to public due to radioactive releases from the entombed structure, which is assumed to be far less effective at containment than a repository. Additionally, the impact on security misappropriation is much greater, since the i-graphite is in a much more accessible form in an entombed reactor compared to a repository. However, the good performance in other criteria causes this option to have the best overall weighted score at this stage of the MCDA assessment when using this weighting allocation.

Currently, the entombed reactor is assumed to require no further monitoring or intervention. See later in the Sensitivity Analysis section for an alternative treatment of this option, which considers a care and maintenance period.

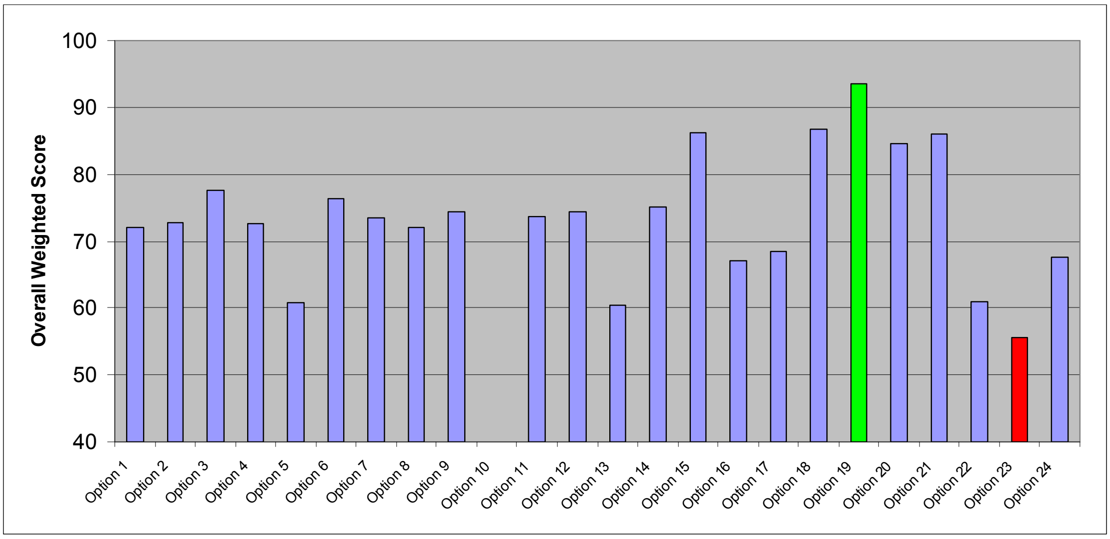


Figure 2 Overall weighted scores for remaining twenty three options based on 'Allocation A – Extreme Weightings'

Figure 3 shows the re-normalised results following the successive removal of the first twelve least-well-performing options (the intermediate results are presented in full in Appendix 1). At all stages between those shown in Figure 2 and Figure 3, Option 19 remains the best-scoring.

Option 19 (In-situ entombment) remains the best performing option. Option 4 (Deferred start with remote retrieval) is now the worst.

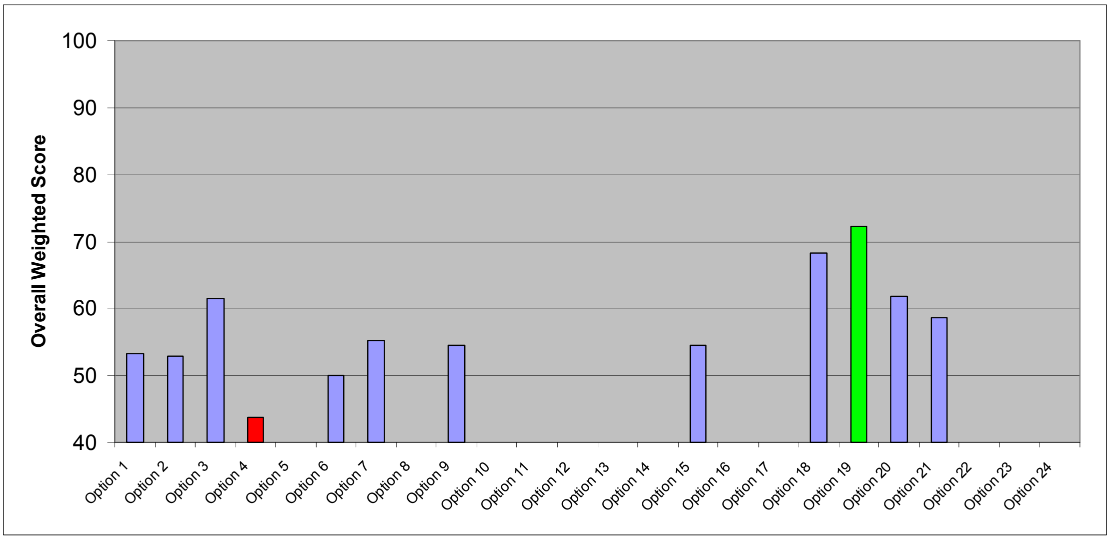


Figure 3 Overall weighted scores for remaining twelve options based on 'Allocation A – Extreme Weightings'

Figure 4 shows the re-normalised results following the successive removal of the first twenty least-well-performing options. It should be noted that the least-well-performing options at this stage of the MCDA assessment are among the best performing options considered initially.

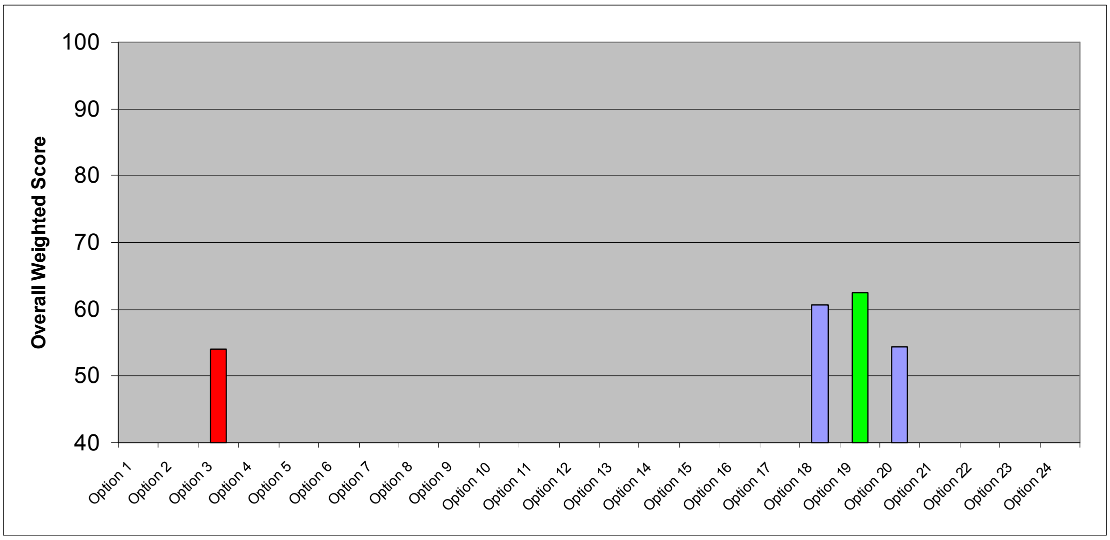


Figure 4 Overall weighted scores for remaining four options based on 'Allocation A – Extreme Weightings'

At all stages between those shown in Figure 3 and Figure 4, Option 19 (In-situ entombment) remains the best performing option.

Option 18 (Graphite re-use for nuclear application only) is the next best performing option. This option diverts a proportion of material away from repository disposal, with associated lower impacts in many criteria, e.g. economic costs, resource usage. During the MCDA workshop, this option was considered to be potentially feasible for small quantities of graphite, but not bulk treatment.

Option 20 (Waste volume reduction and emission to atmosphere) is among the best performing options under this weighting allocation. This option has a large dose to public from the ^{14}C present in the ^{12}C-rich stream that enters the atmosphere for dilution following the gasification stage. However, the smaller quantities of material being sent to a repository reduces the number of transport journeys, the economic costs and the operational cost as a result of risk, causing this option to score well overall.

Option 3 (Minimum processing) is the fourth best performing option under this weighting allocation. This option scores well due to a lower resource usage, lower number of truck journeys and fewer job changes, all due to the fewer processing steps in this option. The impact on public safety via radioactive discharges is greater in Option 3 since the waste is not encapsulated in grout, resulting in greater discharges. During the MCDA workshop it was noted that the packaging of raw i-graphite waste (without the use of an immobilising matrix, such as grout) is likely to be unacceptable in many partner countries due to the voids that would be present, and so this option would be removed using constraints prior to assessment.

3.1 Sensitivity Analysis

3.1.1 Narrow Weightings

The first stage of the sensitivity analysis is to explore the effects of using a narrower, less extreme, range of weightings, which are still consistent with the allocation of high / medium / low to the criteria decided upon during the MCDA workshop. This is referred to as 'Allocation A – Narrow Weightings' and is detailed in Table 3.

Figures 5 to 7 show the overall weighted scores for 'Allocation A – Narrow Weightings' at various stages of the MCDA process. The intermediate results are presented in full in Appendix 2.

Figure 5 shows the overall weighted scores for all twenty four options, based on 'Allocation A – Narrow Weightings'. Compare with Figure 1 to see the effects of using the alternative, narrow weightings.

At this initial stage of the assessment, Option 10 (Alternative retrieval, encapsulation and indefinite storage) is the worst-scoring option (consistent with 'Allocation A – Extreme Weightings').

Option 19 (In-situ entombment) is the best-scoring option, whereas Option 15 was best under 'Allocation A – Extreme Weightings'. The difference in score between Options 19 and 15 is very small, however.

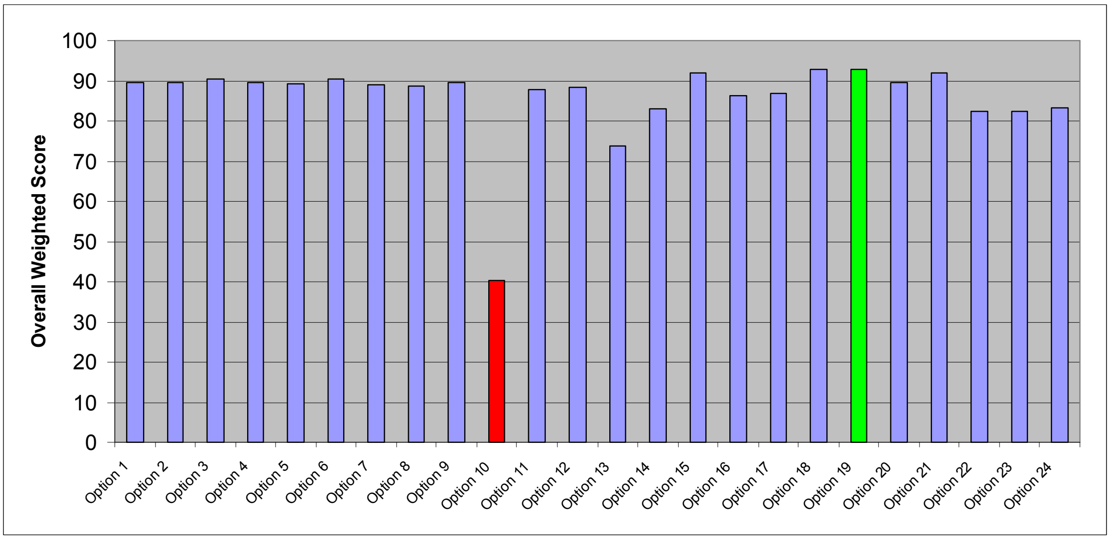


Figure 5 Overall weighted scores for all twenty four options based on 'Allocation A – Narrow Weightings'

Figure 6 shows the re-normalised results following the successive removal of the first twelve least-well-performing options (the intermediate results are presented in full in Appendix 2). Compare with Figure 3 to see the effects of using the alternative, narrow weightings. At this stage of assessment, the effects of extreme weightings vs. narrow weightings are minimal; the best and worst-scoring options are unchanged and the differences between remaining options are small. At all stages between those shown in Figure 5 and Figure 6, Option 19 (In-situ entombment) remains the best-scoring.

Option 4 (Deferred start with remote retrieval) is now the worst-performing option at this stage of assessment (consistent with 'Allocation A – Extreme Weightings').

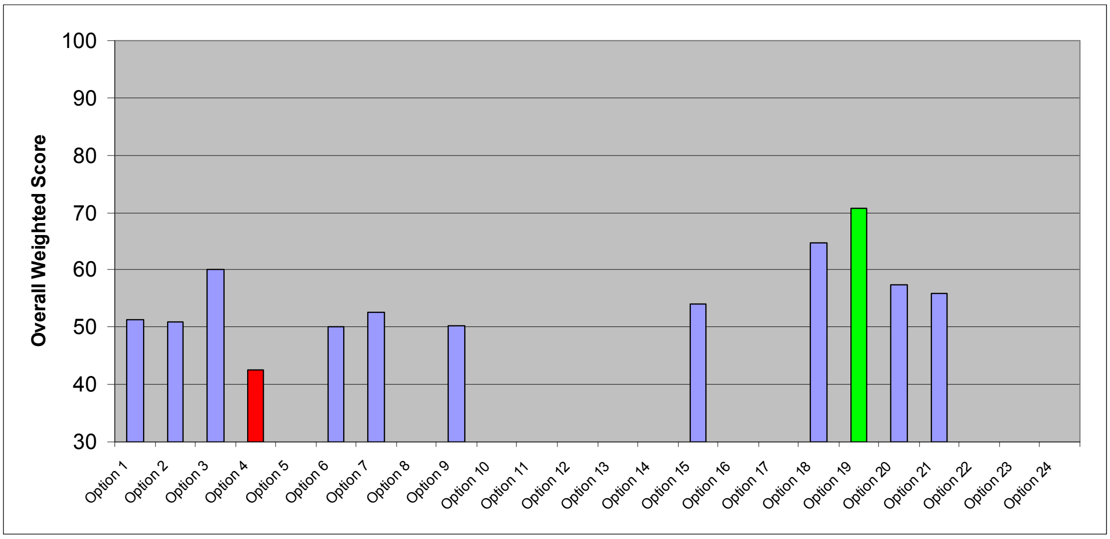


Figure 6 Overall weighted scores for remaining twelve options based on 'Allocation A – Narrow Weightings'

Figure 7 shows the re-normalised results following the successive removal of the first twenty least-well-performing options. Compare with Figure 4 to see the effects of using the alternative, narrow weightings.

Option 19 (In-situ entombment) remains the best-scoring.

Option 3 (Minimum processing), Option 18 (Graphite re-use for nuclear application only) and Option 20 (Waste volume reduction and emission to atmosphere) are the next best performing options. This is consistent with 'Allocation A – Extreme Weightings', although in this case Option 3 is slightly better performing than Option 20.

The effect of using narrow weightings compared to extreme weightings (with the consistent allocation of high / medium / low to each criterion) appears to be minimal in the MCDA process and the identification of preferred options.

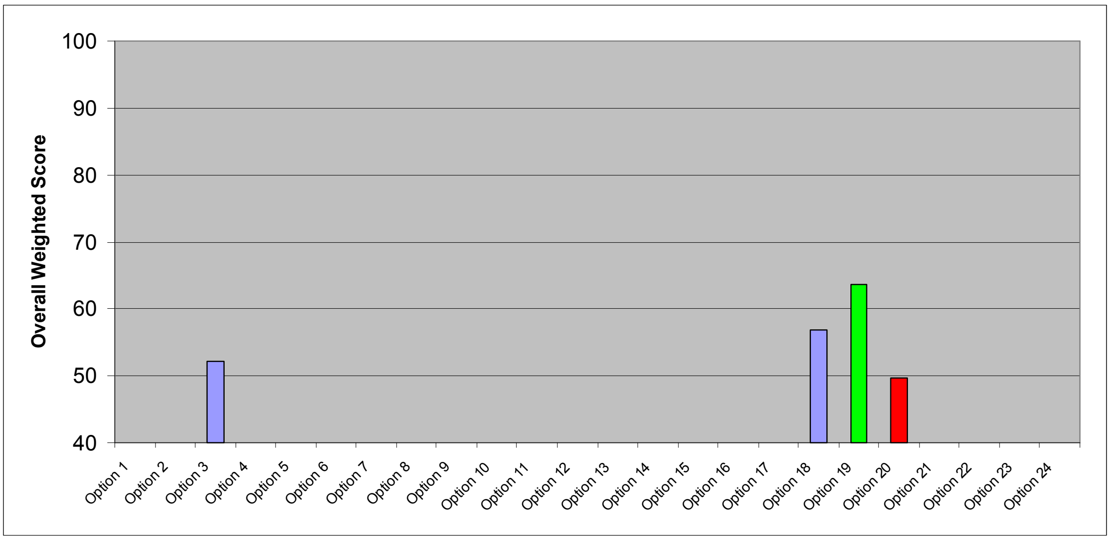


Figure 7 Overall weighted scores for remaining four options based on 'Allocation A – Narrow Weightings'

3.1.2 Alternative Weighting Allocations

Allocation B – Narrow Weightings

The next stage of sensitivity analysis is to apply different weighting allocations (alternatives to those presented in Table 2). This is to investigate the impacts of prioritising the criteria differently to that decided upon in the MCDA workshop, since this is only one of any number of users' options for weighting.

It was noted during the MCDA workshop that it is difficult for CARBOWASTE partners to assign a definitive set of weightings, since the priorities of scientists and engineers are likely to be different to those of governments, regulators or members of the public, for example.

In choosing alternative weighting allocations, an attempt is made to explore the effects of considering the priorities of two different, hypothetical, stakeholders. Hypothetical stakeholder 1 places a high priority on radiological impacts due to discharges, worker safety, hazard potential, security misappropriation and burden on future generations. Hypothetical stakeholder 2 places a high priority on radiological impacts due to discharges, resource usage, hazard potential, economic costs, and concept and operational predictability.

These are represented by 'Allocation B – Narrow Weightings' and 'Allocation C – Narrow Weightings', the details of which are provided in Table 3 and Table 4, respectively. For simplicity, only narrow weighting bands (75 / 50 / 25) are considered for these alternative weighting allocations.

Figure 8 shows the overall weighted scores for all twenty four options, based on 'Allocation B – Narrow Weightings'. Compare with Figure 5 to see the effects of using the alternative weighting allocations.

As with ‘Allocation A – Narrow Weightings’, Option 10 (Alternative retrieval, encapsulation and indefinite storage) is initially the worst-performing option. This time, Option 3 (Minimum processing) and Option 6 (Minimum processing with deferred start) are the equally best performing options, but the differences in scores between these and the majority of other options are small at this stage.

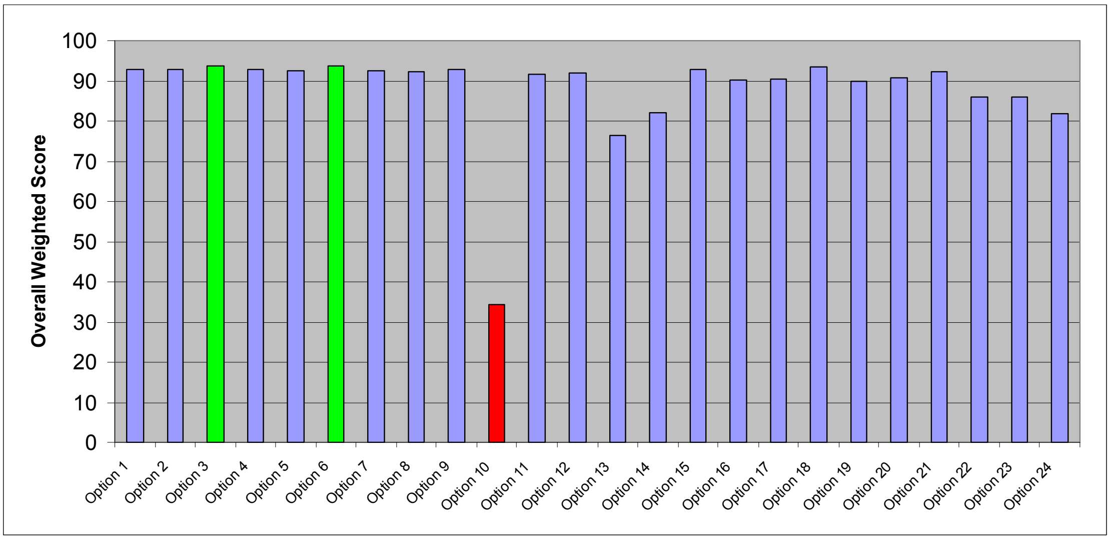


Figure 8 Overall weighted scores for all twenty four options based on ‘Allocation B – Narrow Weightings’

Figure 9 shows the re-normalised results following the successive removal of the first twelve least-well-performing options (the intermediate results are presented in full in Appendix 3). Compare with Figure 6 to see the effects of using the alternative weightings. At this stage of assessment, the effects of the alternative weightings appear minimal. The same twelve options are remaining in the assessment; Option 4 is the least-well-performing option at this stage.

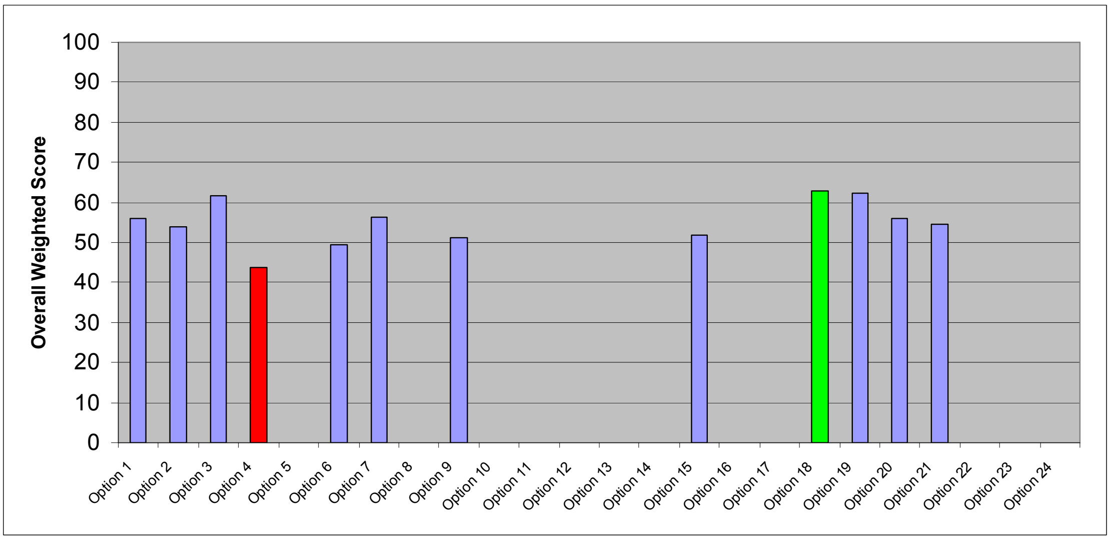


Figure 9 Overall weighted scores for remaining twelve options based on 'Allocation B – Narrow Weightings'

Option 18 (Graphite re-use for nuclear application only) is the best performing option at this stage, compared with Option 19 (In-situ entombment) under 'Allocation A – Narrow Weightings'. Option 19 is the next best performing option at this stage, however.

At the stages of the MCDA process between those shown in Figure 8 and Figure 9, the best-scoring option alternates between Option 18 and Option 19.

Figure 10 shows the re-normalised results following the successive removal of the first eighteen least-well-performing options. It is not possible to remove the worst-performing option and continue the MCDA beyond this stage: once the remaining options have the same value in one or more criteria it is not possible to score them on a linear scale. Compare with Figure 4 to see the effects of using the alternative, narrow weightings.

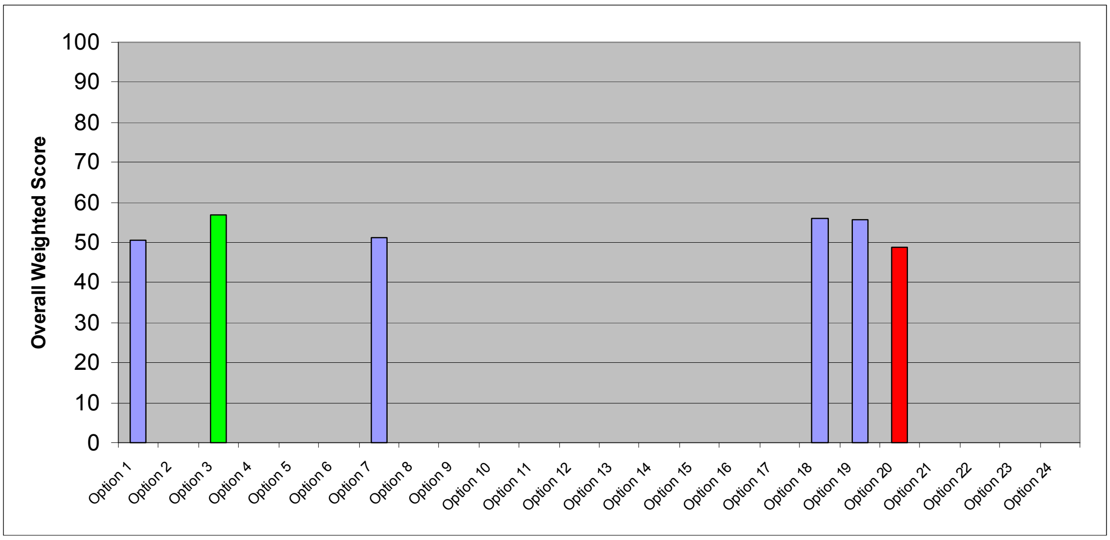


Figure 10 Overall weighted scores for remaining six options based on 'Allocation B – Narrow Weightings'

As with ‘Allocation A – Narrow Weightings’, Option 3 (Minimum processing), 18 (Graphite re-use for nuclear application only), 19 (In-situ entombment) and 20 (Waste volume reduction and emission to atmosphere) are the best performing options. There is little difference between the overall scores of Options 3, 18 and 19.

Allocation C – Narrow Weightings

Figure 11 shows the overall weighted scores for all twenty four options, based on 'Allocation C – Narrow Weightings'. Compare with Figure 5 to see the effects of using the alternative weighting allocations.

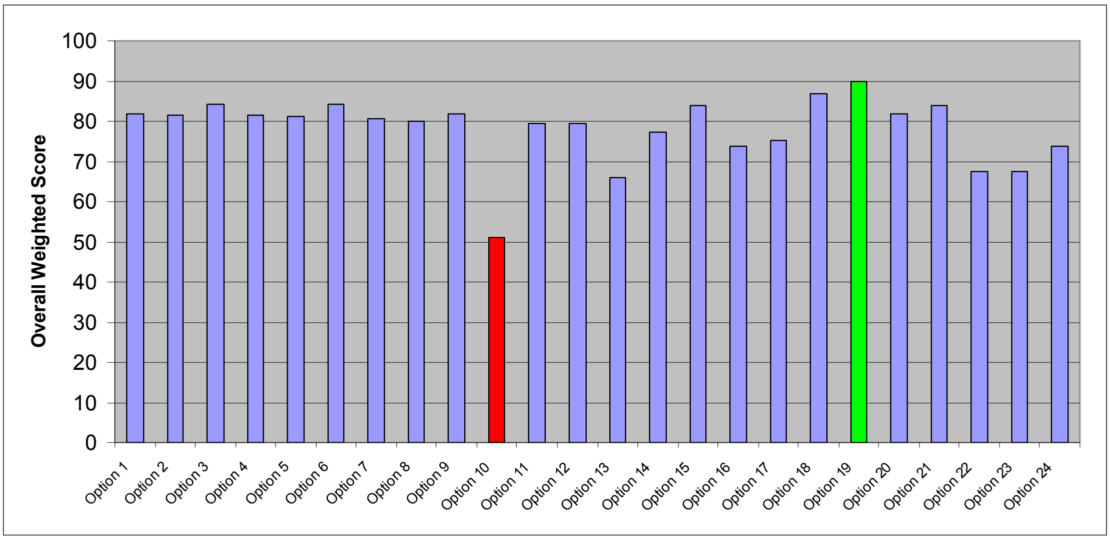


Figure 11 Overall weighted scores for all twenty four options based on 'Allocation C – Narrow Weightings'

As with 'Allocation A – Narrow Weightings', Option 10 (Alternative retrieval, encapsulation and indefinite storage) is the worst-performing and Option 19 (In-situ entombment) is the best performing.

Figure 12 shows that for 'Allocation C – Narrow Weightings' the successive removal of worst-performing options results in the same remaining options at the final stage of the MCDA process as those remaining for 'Allocation A – Narrow Weightings' and 'Allocation B – Narrow Weightings': Option 3 (Minimum processing), 18 (Graphite re-use for nuclear application only), 19 (In-situ entombment) and 20 (Waste volume reduction and emission to atmosphere). The intermediate results for Allocation C are presented in full in Appendix 4.

The use of different weighting regimes appears to have little effect on the selection of preferred options from the twenty four considered in this report. Consistently, Option 10 (Alternative retrieval, encapsulation and indefinite storage) is the worst-performing option.

Following the successive removal of the worst-performing options, Option 3 (Minimum processing), Option 18 (Graphite re-use for nuclear application only), Option 19 (In-situ entombment) and Option 20 (Waste volume reduction and emission to atmosphere) consistently score well.

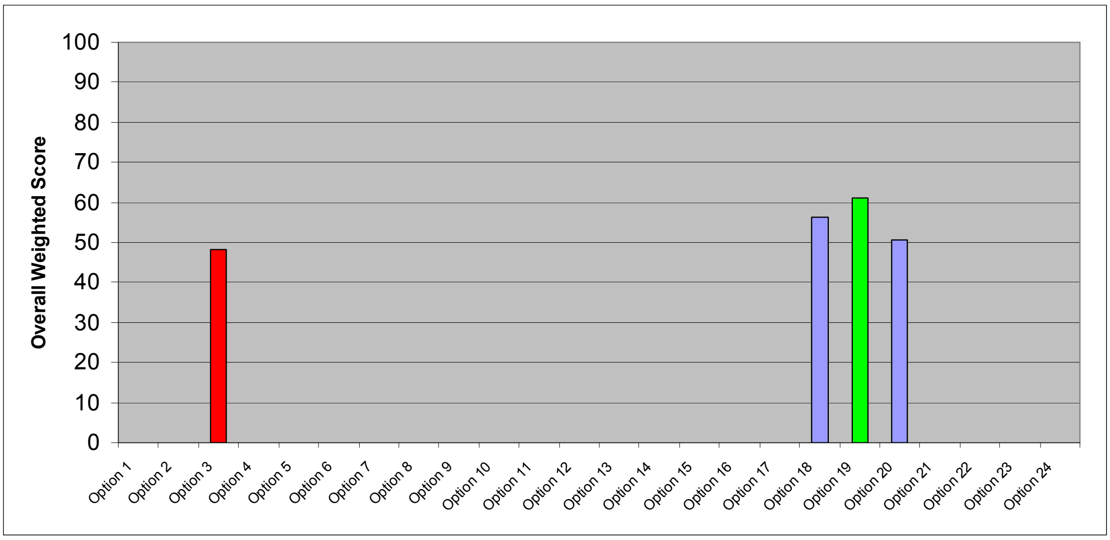


Figure 12 Overall weighted scores for remaining four options based on 'Allocation C – Narrow Weightings'

A further sensitivity study was performed using neutral, or no, weighting, in which each of the criteria had equal influence on determining the overall weighted scores. Again, Option 10 was the worst-performing and Option 19 the best. The results are very similar to those of the weighting allocations already discussed and as such are not included.

3.1.3 Variant Case for Option 19 (In-situ Entombment)

Option 19 (In-situ entombment) scores consistently well throughout the MCDA assessment.

During the MCDA workshop, attendees commented that entombment may not be practically achievable. In some cases, continued care and maintenance would be required, which would make this option similar to Option 10 (indefinite storage). An entombed reactor may require continued, indefinite institutional control even if care and maintenance were not required, which is not currently considered.

Appendix 5 provides a brief review of the entombment concept with consideration of its applicability to i-graphite. An acceptable duration of institutional control for an entombed reactor with i-graphite in-situ is unlikely to reduce radioactivity levels to insignificant levels, due to the long half-lives of ^{14}C and ^{36}Cl. Whilst there is some practical experience of in-situ entombment of legacy nuclear facilities in the United States, the concept has not been applied to a power reactor.

While the assessment presented here considers all twenty four CARBOWASTE options, the limitations of the entombment concept mean that it may be removed from the range of acceptable options (via users' individual constraints) prior to MCDA assessment. Each partner country must make its own assessment as to the acceptability of any particular option.

In order to explore the effects of continued monitoring and maintenance, a variant case of Option 19 was prepared, which included a period of 1,000 years during which workers monitor and maintain the entombed structure.

Effects of including monitoring (by five workers) for 1,000 years for Option 19 are:

- Greater impact on Land use;
- Greater impact on Radiological and Conventional Worker Safety;
- Greater economic cost of employing 5 workers for the monitoring period; and
- Greater burden on future generations.

It can be seen in Figure 13 that Option 19 remains the best-scoring option overall despite the introduction of increased worker safety, land use and cost impacts and a greater burden on future generations. Option 10 remains the worst-scoring option.

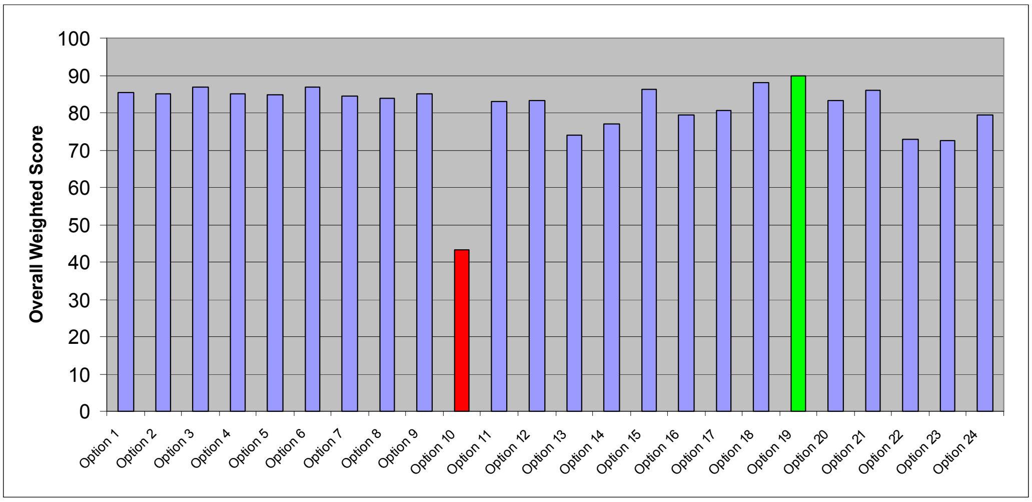


Figure 13 Overall weighted scores for all twenty four options for Option 19 Variant Case based on 'Allocation A – Narrow Weightings'

The process of removing the least-well-performing option and re-scoring the remaining options, as described earlier in the report, was undertaken. It was found that Option 19 became the worst-performing option when twelve options remained (Figure 14) and was removed from the assessment at that stage.

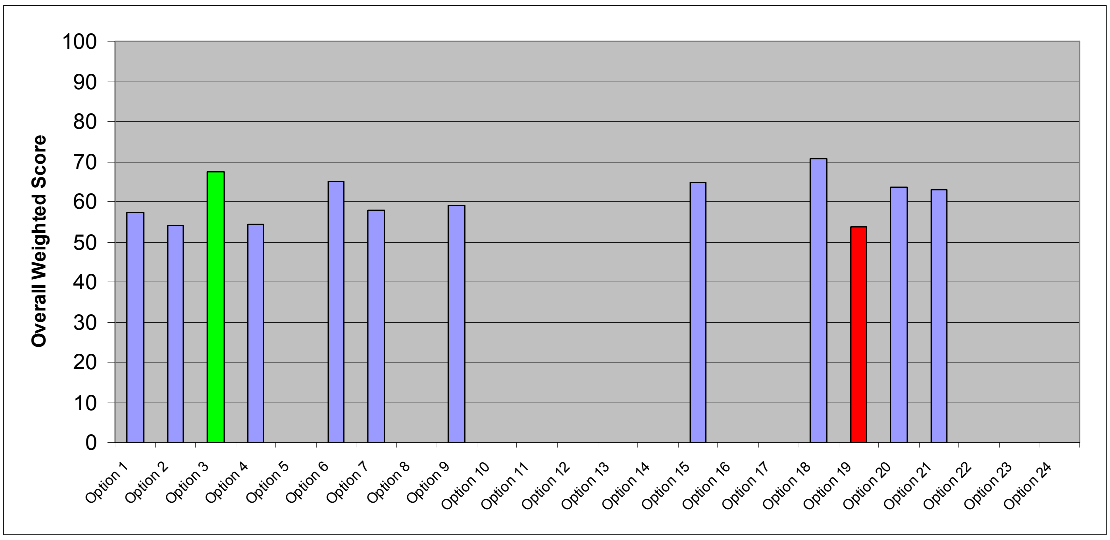


Figure 14 Overall weighted scores for remaining twelve options for Option 19 Variant Case based on 'Allocation A – Narrow Weightings'

Figure 15 shows the Option 19 Variant Case with seven options remaining in the removal process. Option 3 (Minimum processing) is the best-scoring option for this variant case. Compared to Option 1 (Encapsulation and deep repository), it includes a lower resource usage, lower number of truck journeys and fewer job changes, all due to the fewer processing steps in this option. However, the impact on public safety via radioactive discharges is greater in Option 3 since the waste is not encapsulated in grout, resulting in greater discharges. Despite this, it performs best in this variant case.

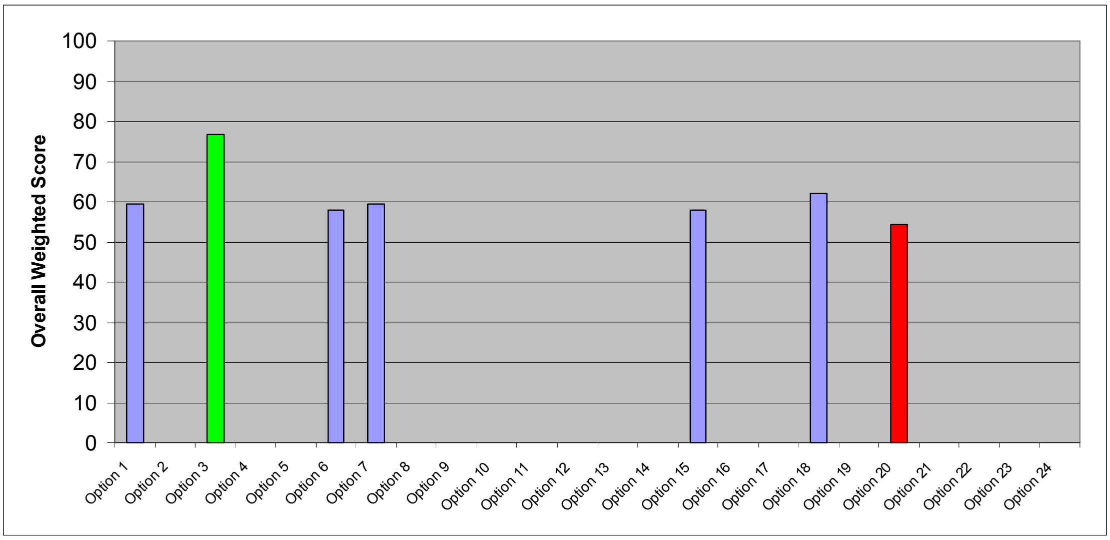


Figure 15 Overall weighted scores for remaining seven options for Option 19 Variant Case based on 'Allocation A – Narrow Weightings'

During the MCDA workshop it was noted that the packaging of raw i-graphite waste considered in Option 3 (without the use of an immobilising matrix, such as grout) is likely to be unacceptable in many partner countries due to the voids that would be present and the increased discharges from the repository that might result.

3.1.4 Summary of Results

Applying extreme vs. narrow weightings appears to have little effect on the narrowing down of the best performing options. The same is true for the application of two example alternative weighting allocations. Option 10 (Alternative retrieval, encapsulation and indefinite storage) is always the worst-scoring option when all twenty four are assessed together.

Option 19 (In-situ entombment) scores consistently well throughout the process.

A variant case for Option 19, which considers a monitoring and maintenance period of 1,000 years produces results that are significantly different. In the first stage of the assessment Option 19 is the best-scoring option, but as the worst-scoring options are successively removed, its relative performance falls and emerges as the worst-performing option part way through the process. Option 3 (Minimum processing) is the best performing option in this case.

4 Qualitative Assessment of Case Studies 2 and 3

This section examines the twenty four options with reference to their applicability to graphite in a vault (Case Study 2) and a research reactor (Case Study 3). A commentary on the potential differences between results for Case Studies 1, 2 and 3 is provided.

Each of the twenty four options was examined to identify particular stages that could not be applied, or would require significant modification to apply, to Case Study 2 (graphite in vault) or Case Study 3 (research reactor). It was noted that the first stage in all options: 'Graphite in Core' will not be applicable to graphite in a vault, as this has already been removed from the reactor. However, a decay-storage period may still be applied, and methods for removing the graphite from the vault for treatment (equivalent to the 'Retrieval' stage) will need to be considered.

Options of particular interest following assessment are:

- **Option 7: Alternative retrieval and graphite form in package**

The method of retrieval for this option is particulate (nibble and vac). It is unlikely that such a method would be applied to the retrieval of graphite from a storage vault, and therefore this option would not differ from Option 1 in Case Study 2.

- **Option 8: Alternative retrieval and repository**

Graphite material is retrieved under water in this option. It is not anticipated that such a method would be either appropriate or possible for graphite in a vault or research reactor, and therefore this option would not differ from Option 9 in Case Studies 2 and 3.

- **Option 10: Alternative retrieval, encapsulation and intermediate storage**

As for Option 7, the particulate retrieval method is unlikely to be applied to graphite in a vault.

- **Option 11: In situ treatment and near-surface repository**

In-situ heat treatment involves running the reactor at a high temperature to condition the graphite. This is clearly not an option for retrieved graphite in a vault and may be neither practicable nor possible for the majority of research reactors.

- **Options 13, 14 and 15: Gasification and isotopic dilution**

Particulate retrieval, which is used in these options, is unlikely to be applied to graphite in a vault. However, the subsequent processes in these options may be a more favourable solution for vault or research reactor graphite where volumes and activities are low, than for a large volume of higher-active graphite from a suite of commercial reactors.

- **Options 16 and 17: ^{14}C re-use**

Particulate retrieval, which is used in these options, is unlikely to be applied to graphite in a vault. However, the subsequent processes in these options may be a more favourable solution for specific vault or research reactor graphite with low volumes and high ^{14}C content, than for a large volume of graphite from a suite of commercial reactors.

- **Option 18: Graphite re-use for nuclear application only**

This option could be applied to graphite from all three case studies, but may be a more favourable solution for low volumes of graphite with specific characteristics from research reactors.

- **Option 19: In-situ entombment**

This option is not applicable to graphite in a vault (Case Study 2) and is unlikely to be an acceptable or achievable solution on a large scale for a suite of commercial reactors. However, there is some potential for this option to be favourable on a small scale (and therefore to a research reactor – Case Study 3).

- **Option 20: Waste volume reduction and emission to atmosphere**

Particulate retrieval, which is used in this option, is unlikely to be applied to graphite in a vault. However, the subsequent processes in this option may be a more favourable solution for vault or research reactor graphite where volumes and activities are low, than for a large volume of higher-active graphite from a suite of commercial reactors.

- **Option 21: Make use of graphite as inert filler, removing the need for some encapsulation**

Particulate retrieval, which is used in this option, is unlikely to be applied to graphite in a vault. However, this option may be a more favourable solution for vault or research reactor graphite where volumes and activities are low, than for a large volume of higher-active graphite from a suite of commercial reactors.

- **Options 22 and 23: Immobilise / chemically bind ^{14}C**

These two options are likely to be highly energy intensive and hence unlikely to be practicable for large-scale application. It is considered, therefore, that these options may be a more favourable solution for small volumes of graphite with higher levels of activity, which may make them a suitable solution for graphite from specific research reactors (Case Study 3).

4.1 Points for Consideration with Case Study 2 (Vault)

Graphite waste in a storage vault has already been retrieved from the reactor, therefore the early stages of the options (quiescent storage and retrieval) are not applicable, although it is conceivable that graphite could be left in the vault for a number of decades for radioactive decay (and in some cases already has). There may be, however, a strong driver from regulators to deal with wastes held in silos (e.g. such as at Sellafield and Vandellos) as these are often legacy wastes of higher hazard potential, held in aging facilities where total containment may be difficult or expensive to maintain.

Graphite in a vault is likely to be more accessible and in smaller pieces than in-reactor graphite, and therefore the methods used for the retrieval of vault graphite will differ considerably. It is anticipated that vault graphite retrieval will be, for example, by mechanical grab (e.g. such as the petal grab used at the Vandellos silos) rather than the drill-and-tap or nibble-and-vac methods proposed for reactor graphite.

In most cases the retrieval of graphite from a reactor will not be carried out as an isolated project, and the methods chosen for retrieval, treatment and disposal will need to take into account both the wider site waste management strategy and the safety functions of the reactor configuration. Graphite stored in vaults and silos might be an exception to this, and therefore more flexibility in the processes and their order of execution may be available. However, graphite in silos may be mixed in with other contemporary wastes (e.g. metal components) which may require separation to enable particular treatment and disposal options to be viable. If segregation of such mixed wastes were either not possible or economically viable then the treatment and disposal methods employed would need to encompass all waste components, potentially ruling out a number of treatment and disposal options that would be otherwise viable for a graphite-only waste stream. Additionally, some vaults may contain water, and therefore treatment methods accounting for partially-wetted or saturated graphite may need to be considered.

The option of reactor entombment would not be applicable to graphite wastes stored in a vault. This option was developed to remove the need for retrieval from the reactor, which in the case of vault graphite has already occurred.

4.2 Points for Consideration with Case Study 3 (Test Reactor)

Typically, a test reactor will have a smaller inventory of graphite (volume and activity) than a commercial reactor, and therefore the range of potential treatment and disposal options may be larger than for a commercial reactor. Some of the options involving high energy usage (e.g. encapsulation in impermeable media) that may be uneconomical for the treatment of large volumes of graphite could be applied to the small volumes of graphite arising from a test reactor, assuming such treatment was shown to be required. However, it should be noted that graphite from a test reactor may have very specific characteristics (e.g. specialised geometries) and may have had a purpose other than moderation (e.g. shielding/reflection) which may influence the choice of technique for retrieval and/or treatment.

The location of a test reactor may be an issue. Commercial reactors are often situated in relatively remote areas within their own licensed land. This may therefore provide the necessary space to construct retrieval and treatment facilities, interim stores and even allow for entombment. Test reactors on the other hand, although smaller, are often located within more congested areas on sites that may be largely unlicensed (e.g. universities or research facilities). This may therefore limit the space for waste treatment and storage facility construction or general access for decommissioning works.

The impact on employment of decommissioning is likely to be significantly smaller for a test reactor than for a commercial reactor. An individual test reactor will employ fewer people than a commercial reactor and may be just one component of a large and diverse research campus, thereby facilitating the redeployment of staff to other operations after decommissioning.

There is practical experience of decommissioning test reactors containing i-graphite (e.g. GLEEP, WAGR) from which learning can be drawn upon and applied to future projects.

5 Conclusions

MCDA assessments have been undertaken to determine best and worst-scoring options for the management of i-graphite from a starting position of twenty four options. A number of sensitivity cases have also been examined to determine the effects of various normalised scoring and weighting configurations.

The assessments presented in this report follow on from an initial assessment of the selected MCDA process, as presented in Wareing *et al.* (2013). That report presented a detailed analysis of the impact of each option on each criterion, but did not allow for a direct comparison of options, which requires a normalised scoring and weighting process.

The purpose of the MCDA assessment presented here and in Wareing *et al.* (2013) is to identify and test a process than can be utilised by the CARBOWASTE partner countries. It is not possible to select a preferred option for all countries, since each will have its own specific national strategies, constraints and regulations that will preclude certain options from being viable.

It has been shown that, due to the wide ranges of outputs considered, a small number of very poorly performing options can initially cause a large number of the best performing remaining options to appear to be equivalent in performance. A process of continual removal of the worst performing options and renormalisation has allowed the differences between remaining options to be assessed in more detail.

When assessing all twenty four options considered by the CARBOWASTE project (and not removing any based on constraints), Option 19 (in-situ entombment) performs best and Option 10 (indefinite storage) performs worst for Case study 1 (power reactor).

A brief review of the entombment concept has been carried out, identifying some of its limitations when applied to i-graphite. While there is some experience regarding entombment, or in-situ decommissioning, of legacy nuclear facilities in the United States, and as a temporary solution for acutely damaged reactors, the approach of long-term entombment has not been applied in practice to power reactors. As such, it is not a technically proven solution and would likely require significant technological development before a safety case could be demonstrated for its use in immobilising i-graphite in-situ. By including this option within the twenty four assessed here, it is assumed that this concept is viable, which may not be the case in reality for any individual member state.

Options that avoid the use of a deep geological repository perform 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 member states' national strategies, however. For example, if a geological repository were to be constructed solely for the disposal of i-graphite, the complete allocation of the repository's impacts to i-graphite would likely 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. The assumptions and scaling of repository impacts to i-graphite made in this assessment are detailed in Wareing *et al.* (2013).

Options that include the use of a deep geological repository perform moderately well in this assessment due to the improved radiological discharges, hazard potential and security impacts balanced against the negative impacts of repository construction. The worst scoring options are those which consider large, repeated construction activities, such as many treatment facilities or indefinite storage.

Different weighting systems have been applied to examine the effects of varying the impact of each criterion in determining the overall weighted score. It was found that, for the twenty four options considered here, the different weighting allocations had little effect in determining the relative rankings.

A qualitative assessment has been undertaken for Case studies 2 and 3 (i-graphite in a vault/silo, and a research reactor). Each of the twenty four options was examined to identify particular stages that could not be applied, or would require significant modification to apply, to Case Study 2 or Case Study 3. It was noted that, other than the early process stages in all options: e.g. 'Graphite in Core' and 'Retrieval' not being applicable to graphite in a vault, the majority of options remain appropriate for each of the three Case Studies, although specific practicalities for application may vary slightly.

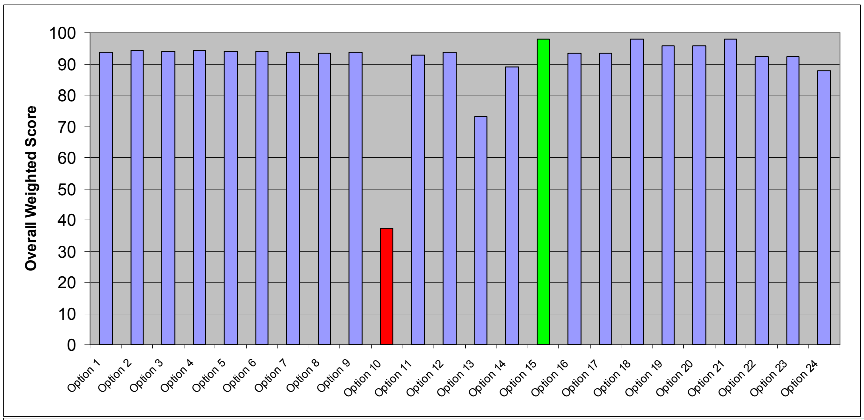
The process presented here has shown that linear additive method of MCDA described is suitable for assessing CARBOWASTE options. However, it is not possible to state here which option is best for any individual member state. Individual member states can use the tools and processes presented here to determine their own best option by applying their own scores, weightings and constraints. The 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 context many more factors that cannot be represented quantitatively, such as national strategies, regulatory approval or public acceptability.

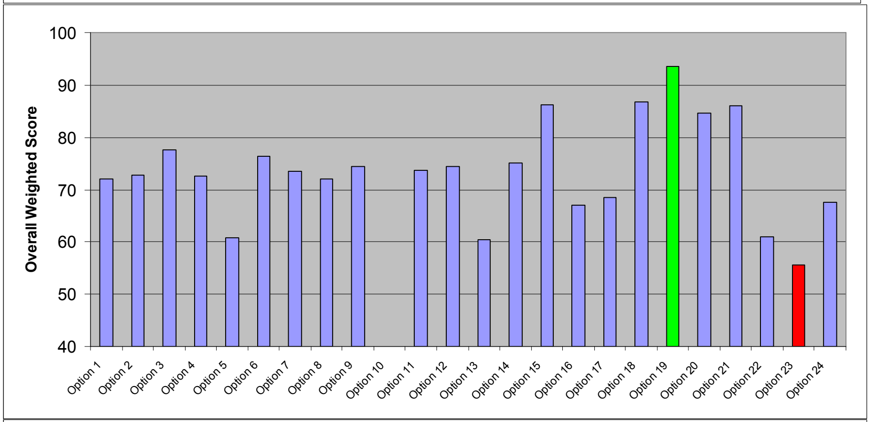
6 References

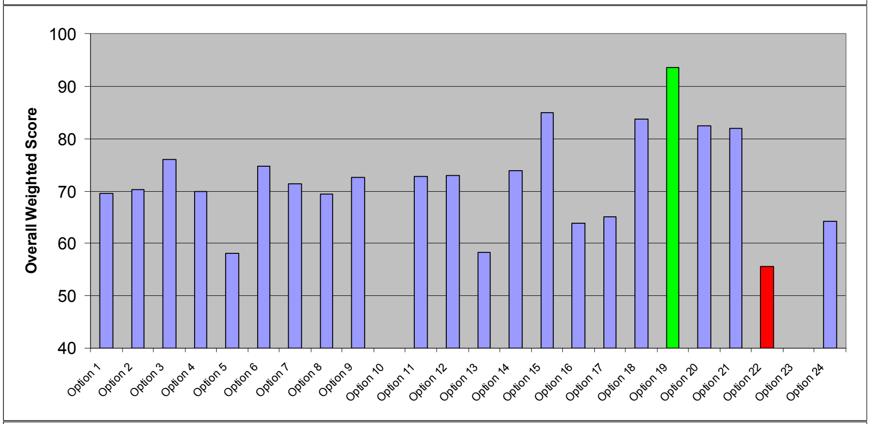
Abrahamsen, L., 2013. WP1 January 2013 MCDA Workshop Minutes. CARBOWASTE-1302-D-1.5.3

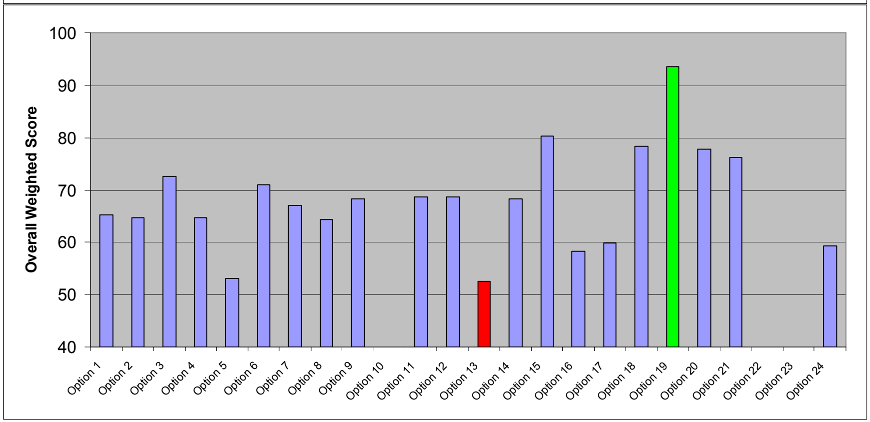
Wareing, A.S., Abrahamsen, L., Jarvis, R.B. and Metcalfe, M., 2013. MCDA Assessments. Carbowaste-1303-D-1.5.3

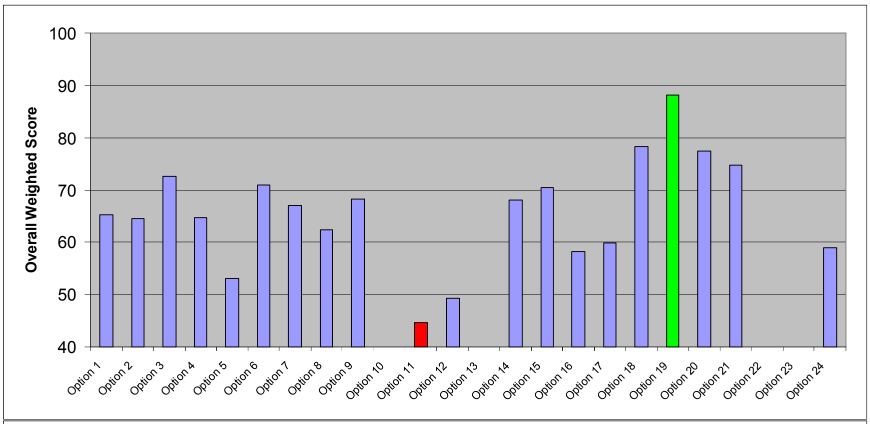
Appendix 1 – Allocation A – Extreme Weightings Results







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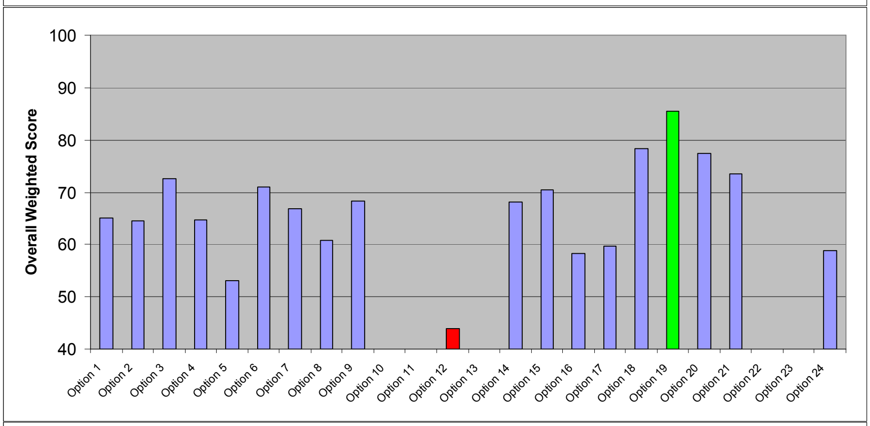
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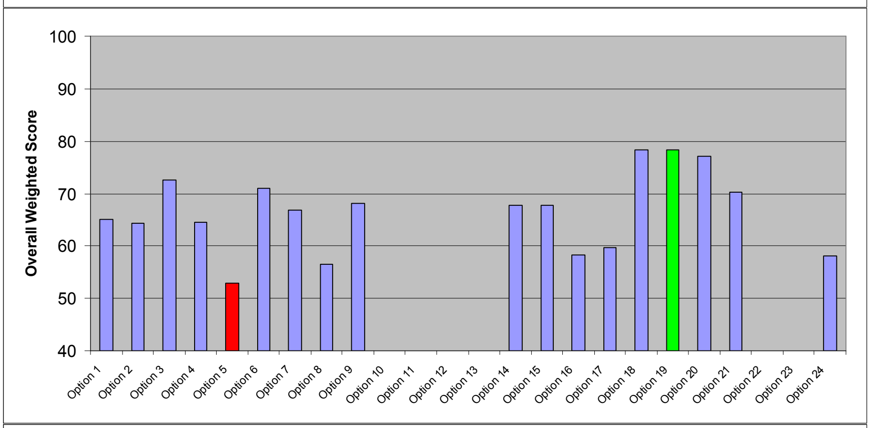
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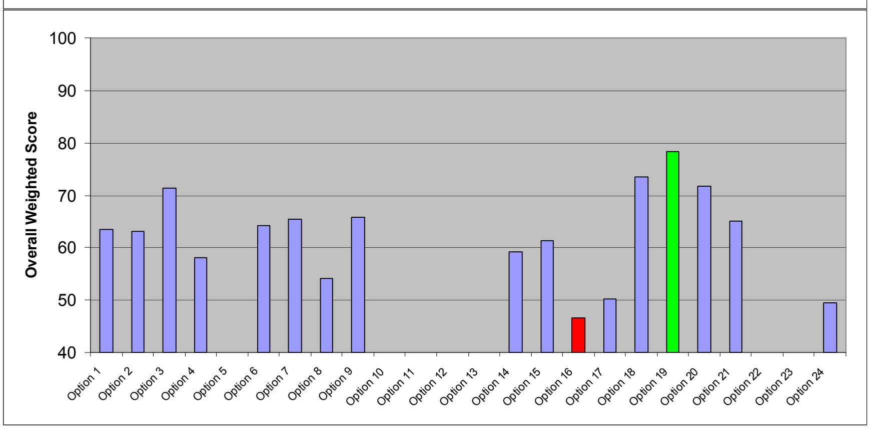
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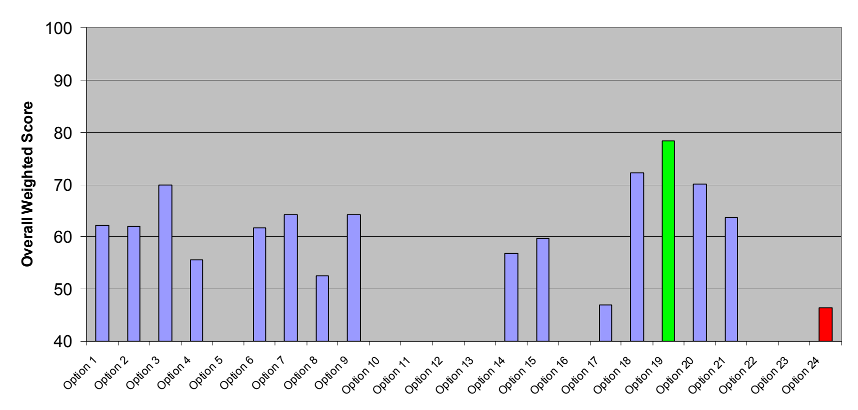
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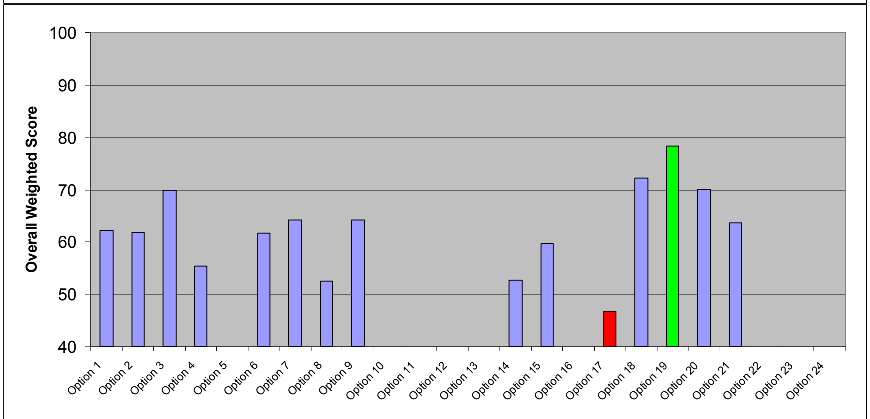
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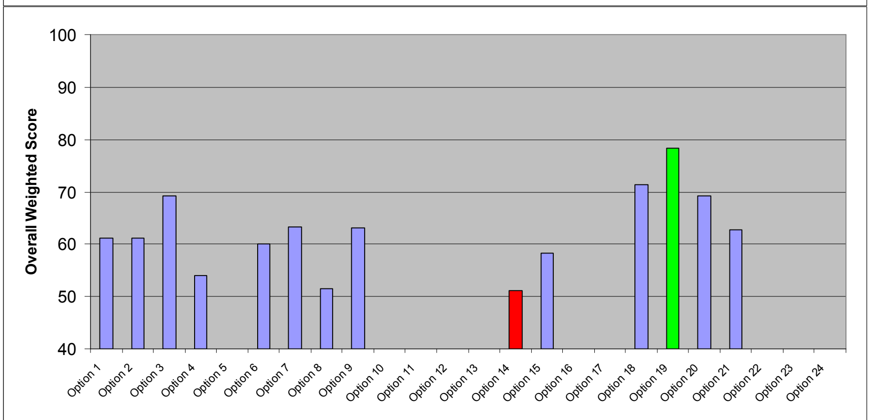
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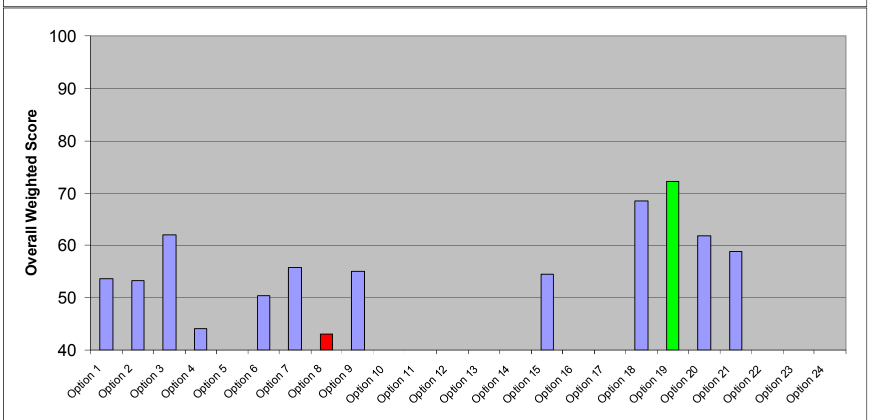
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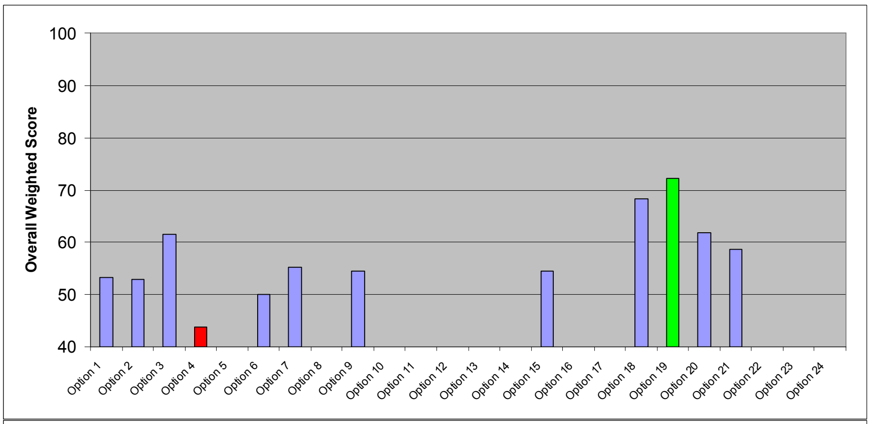
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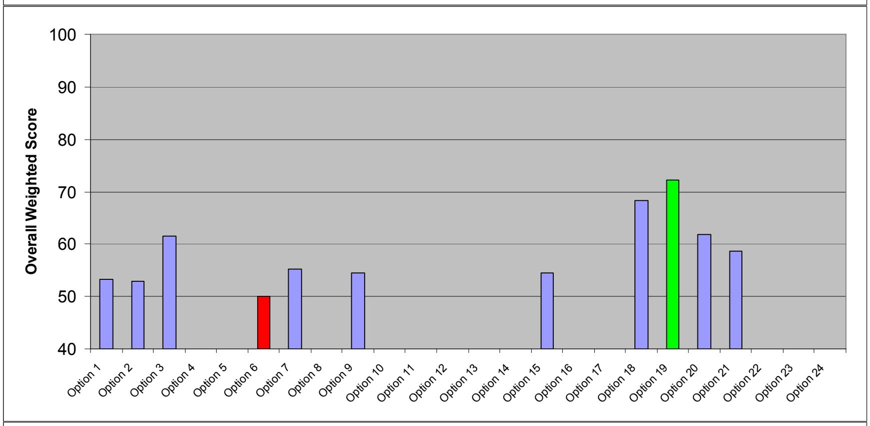
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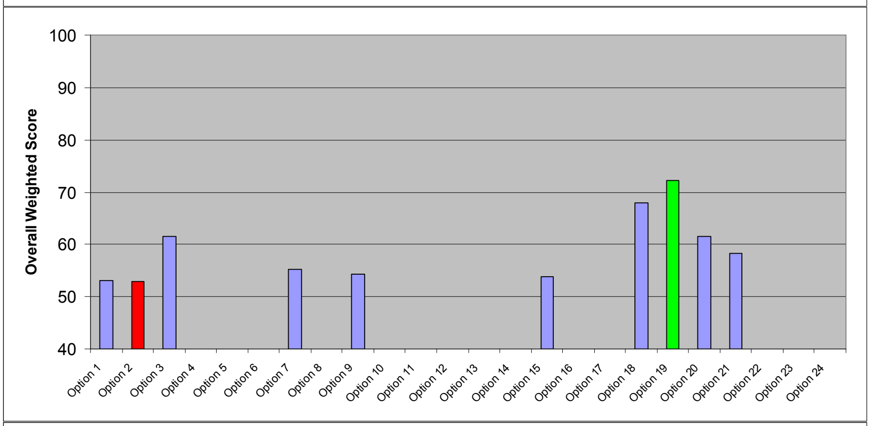
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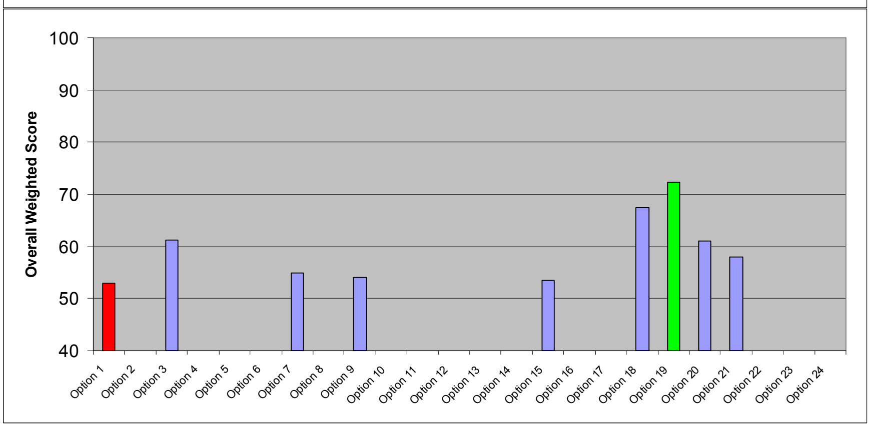
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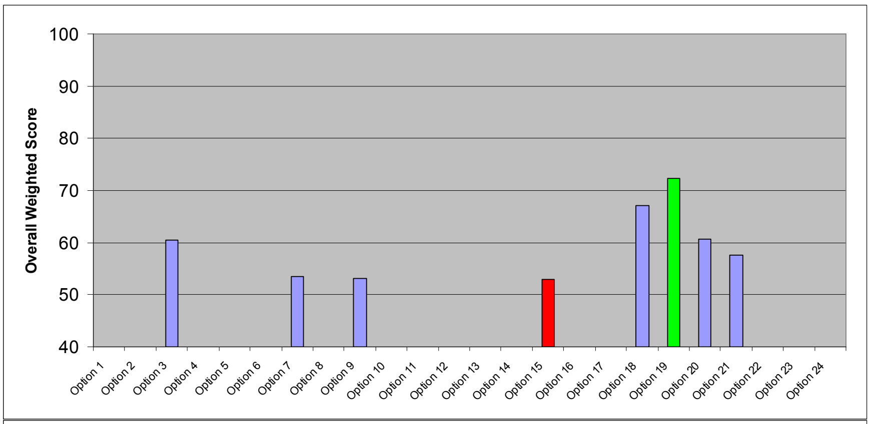
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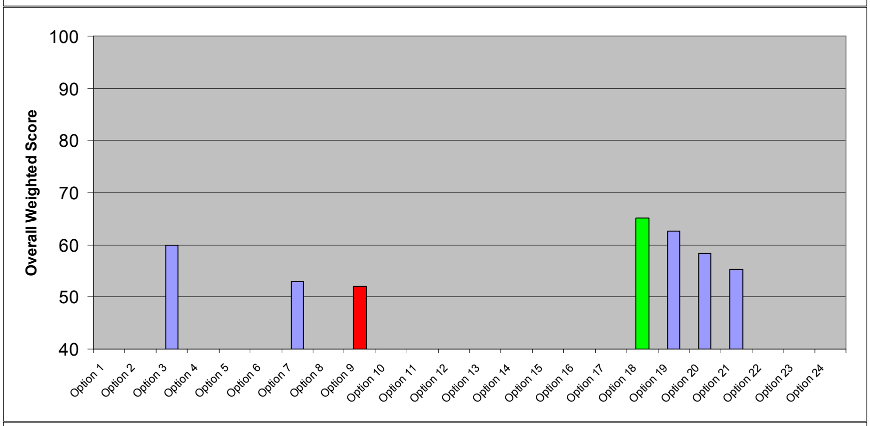
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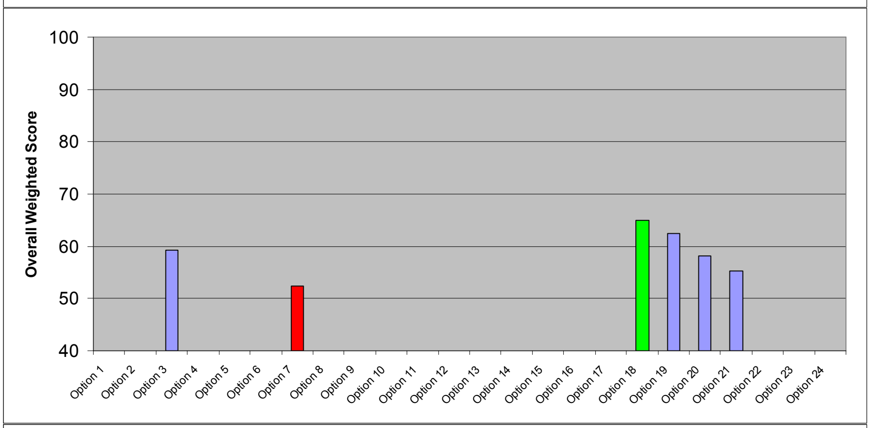
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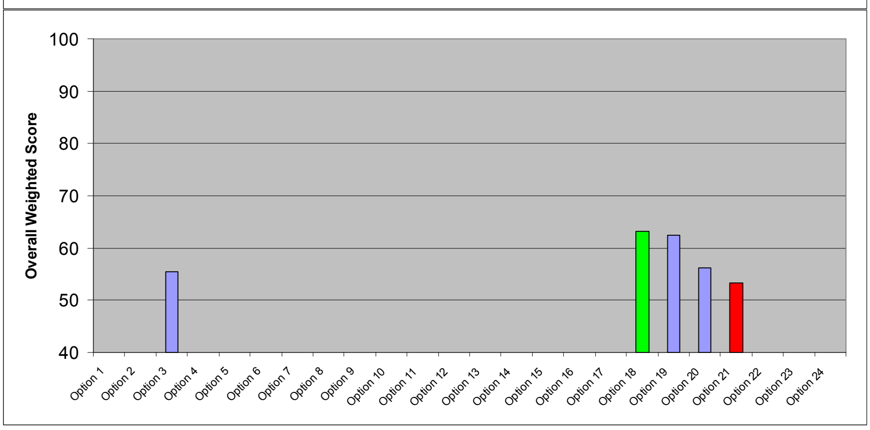
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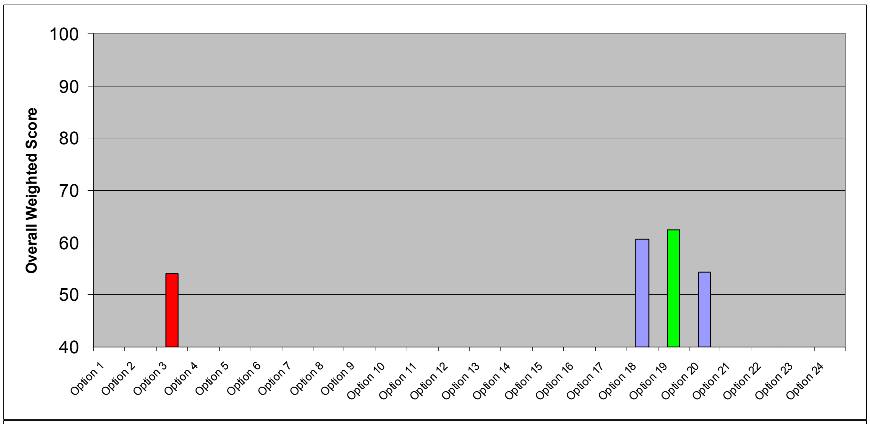
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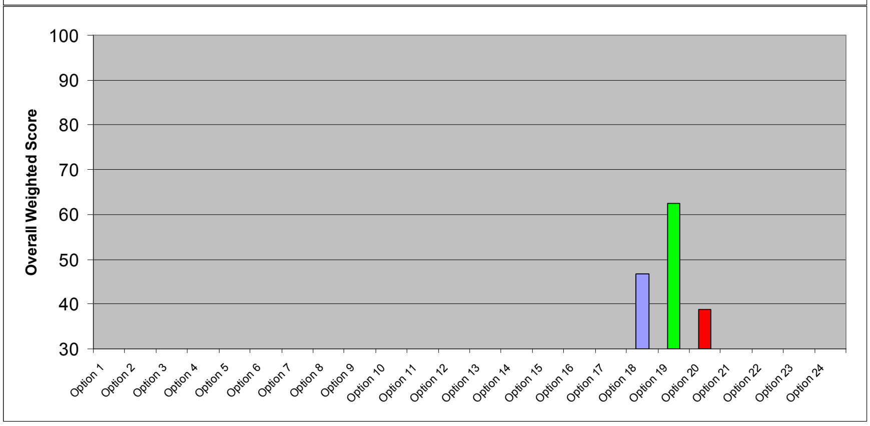
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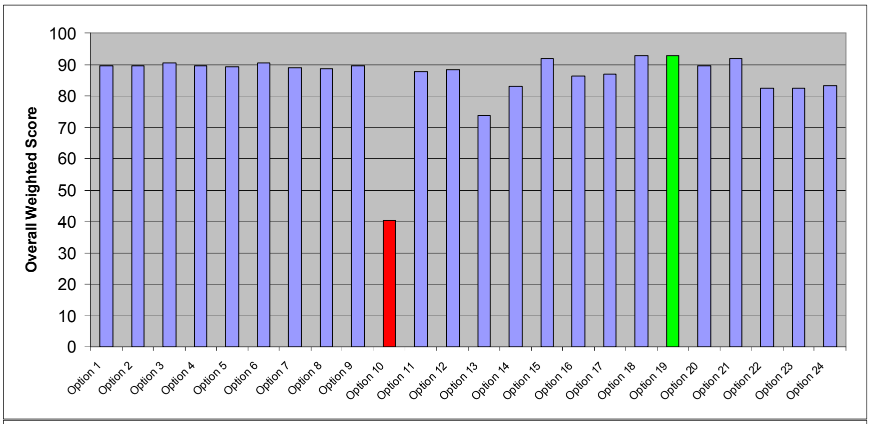
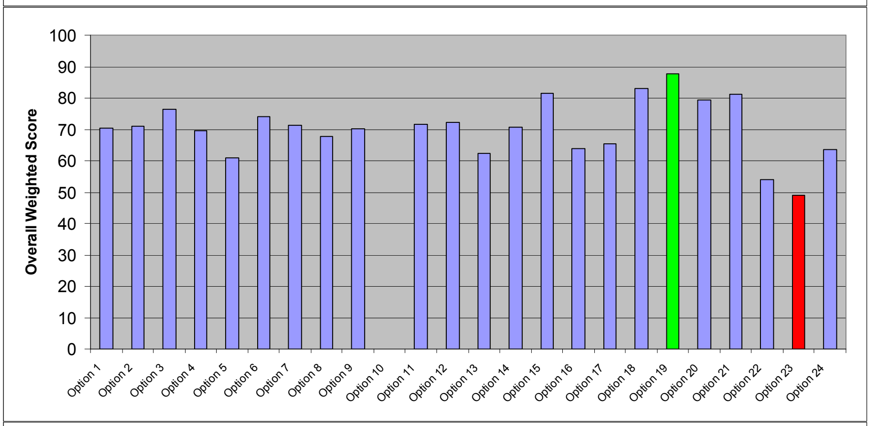
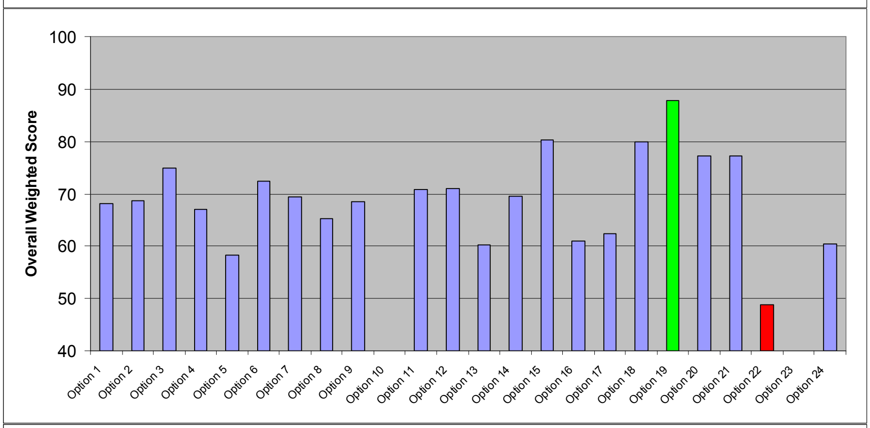
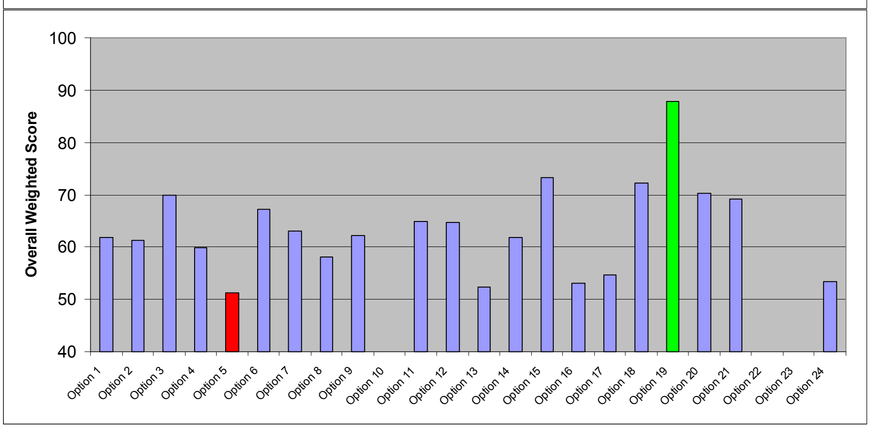
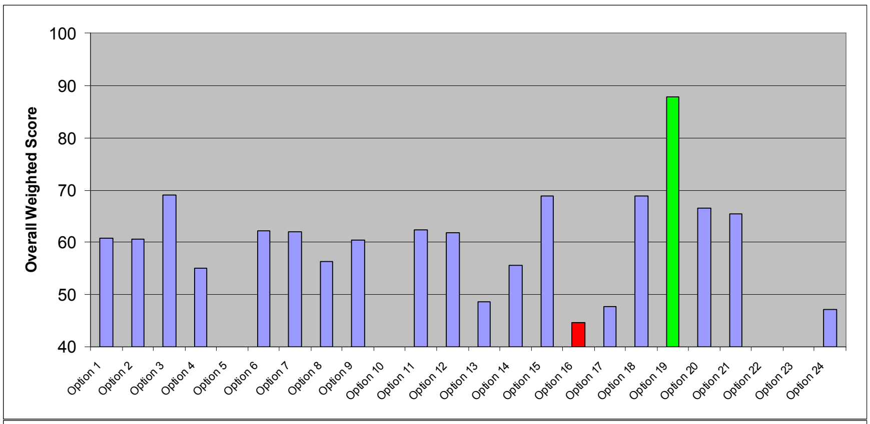
Appendix 2 – Allocation A – Narrow Weightings Results







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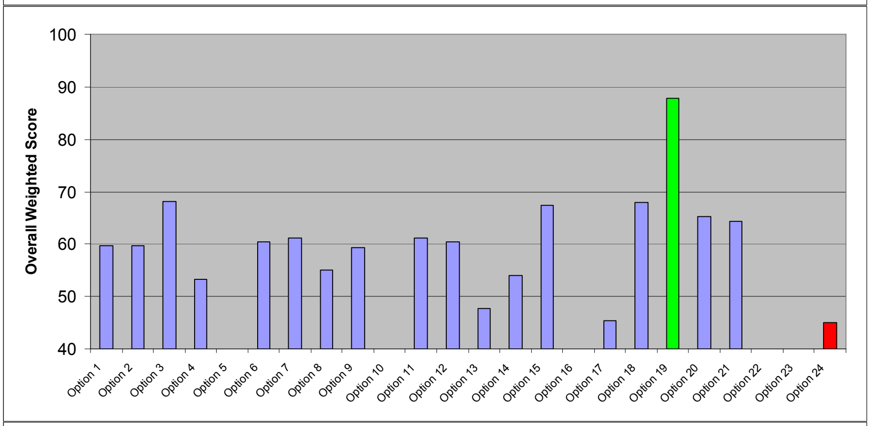
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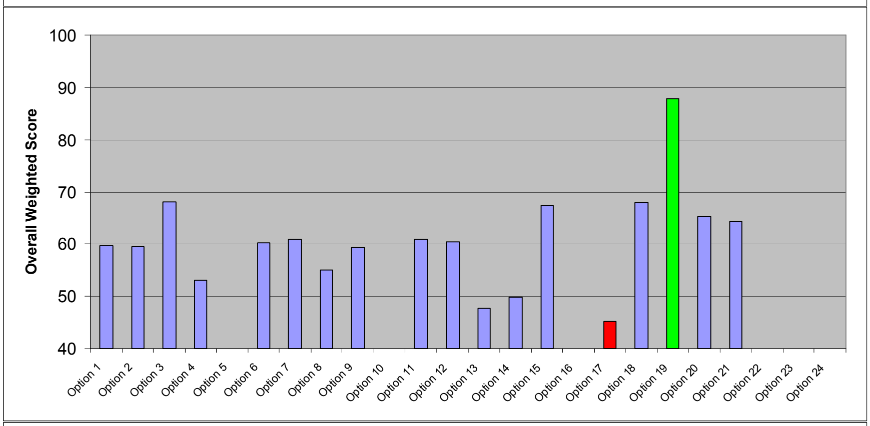
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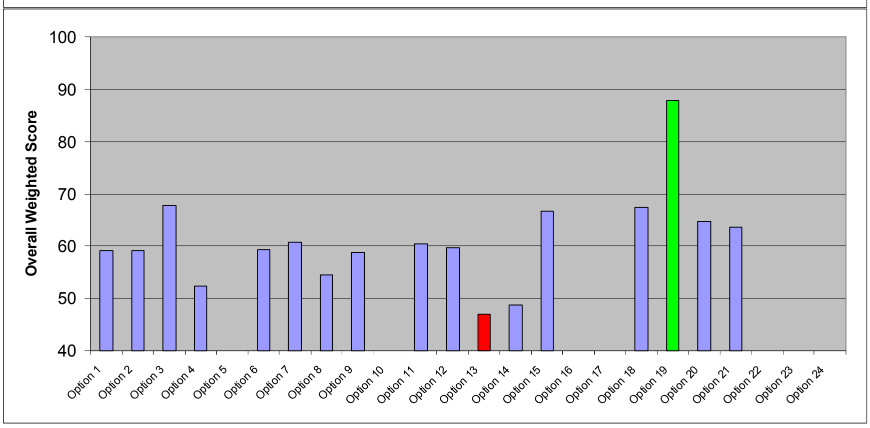
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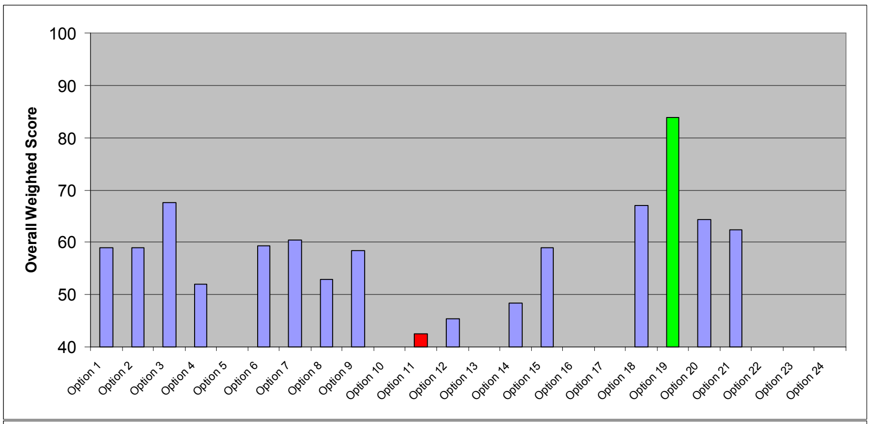
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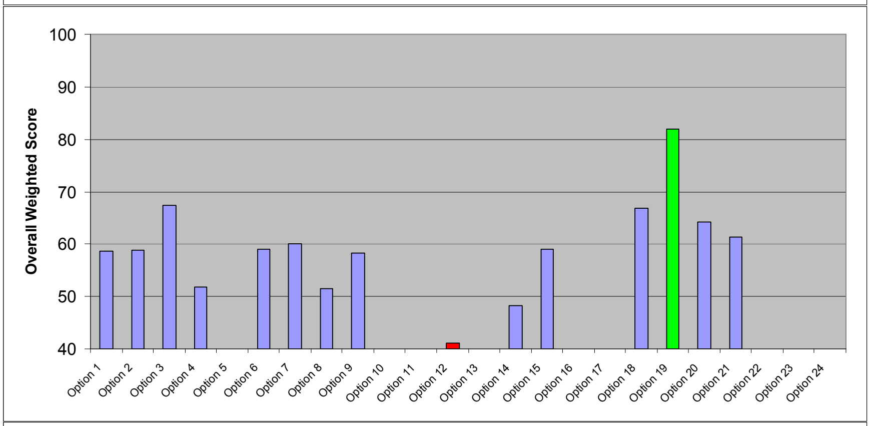
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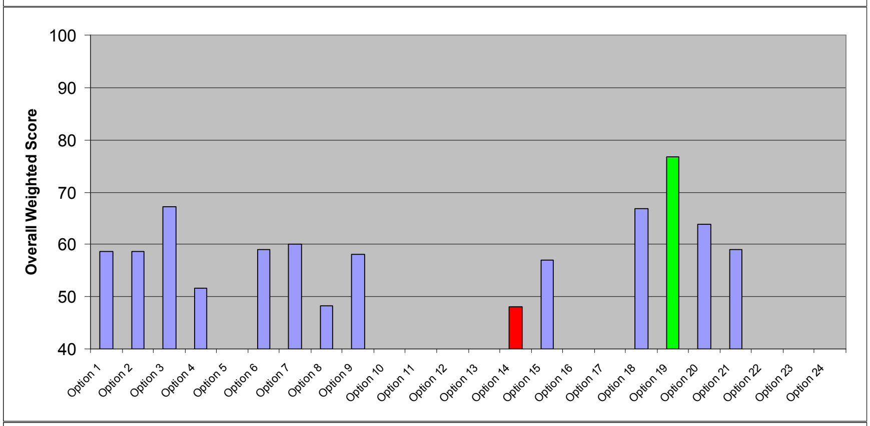
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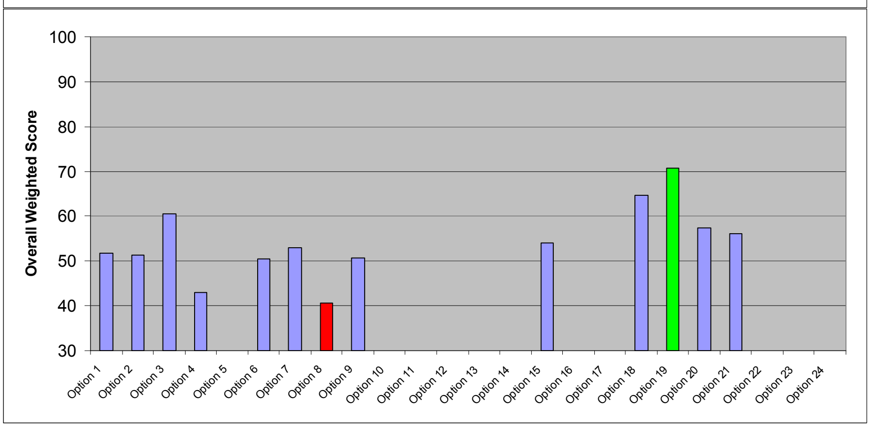
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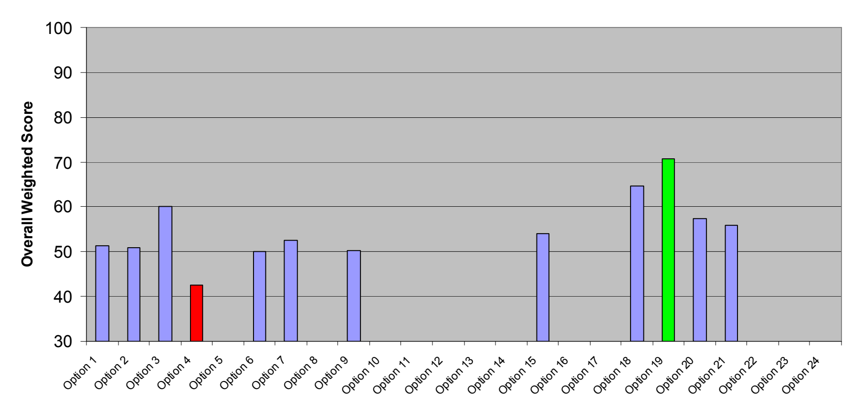
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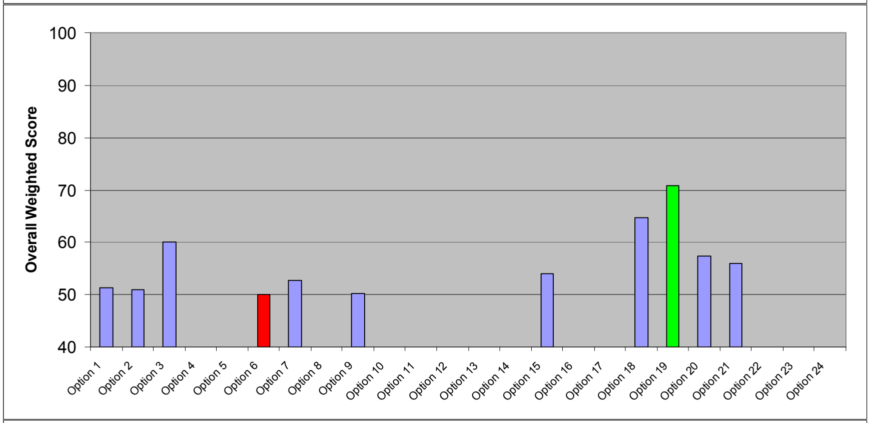
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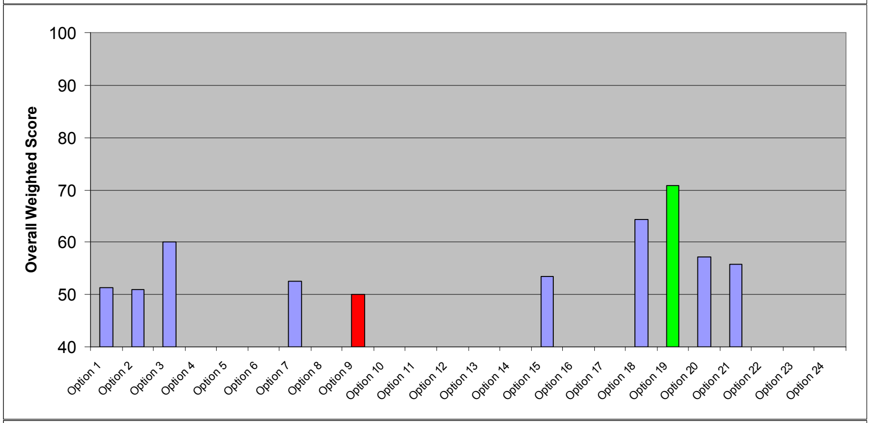
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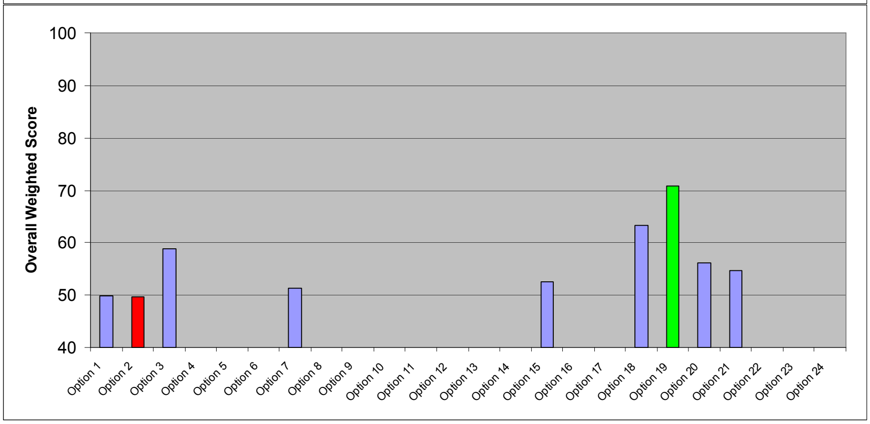
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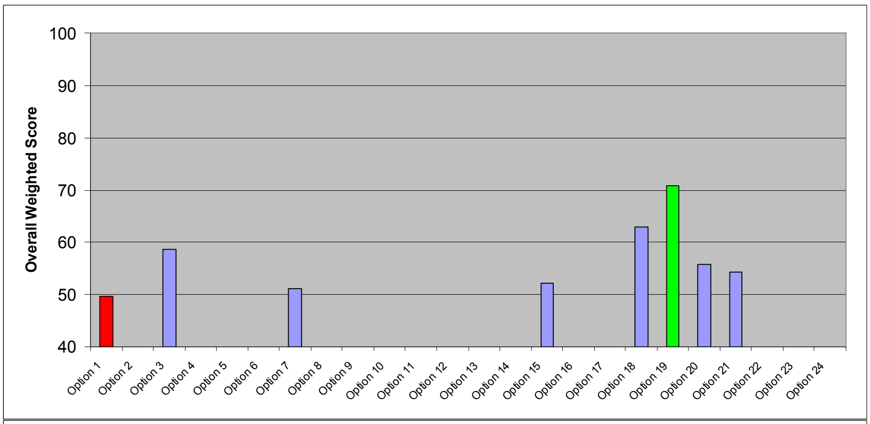
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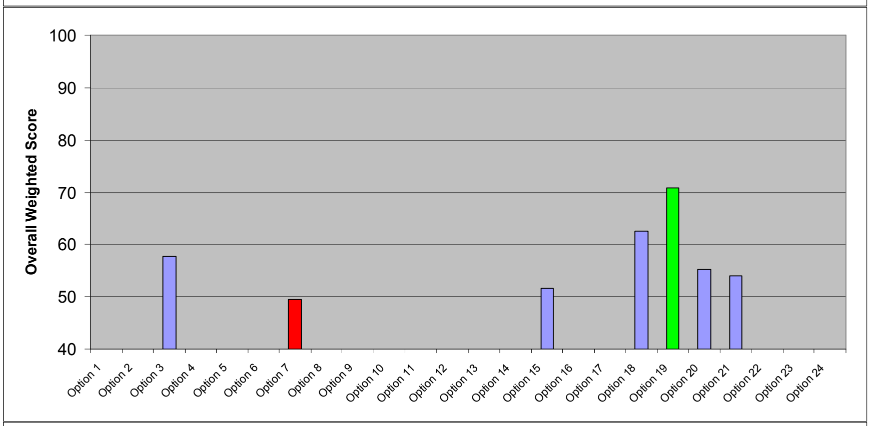
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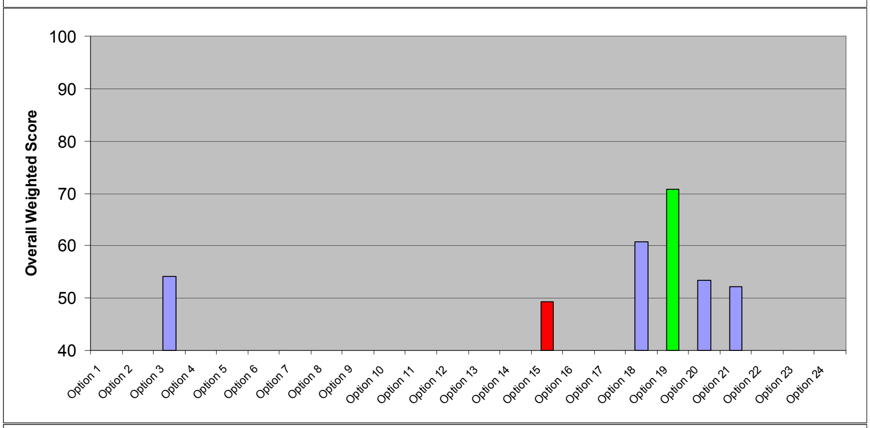
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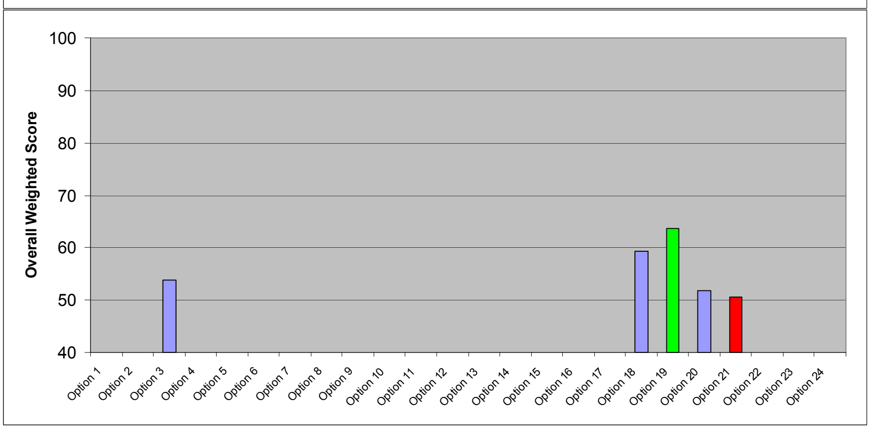
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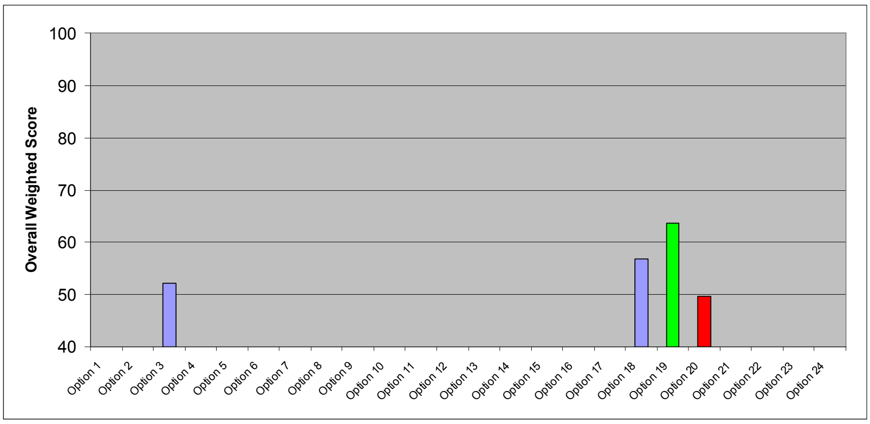
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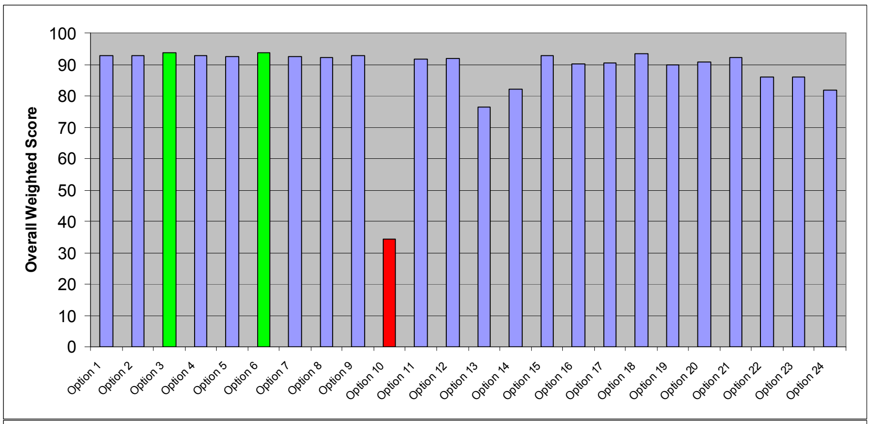
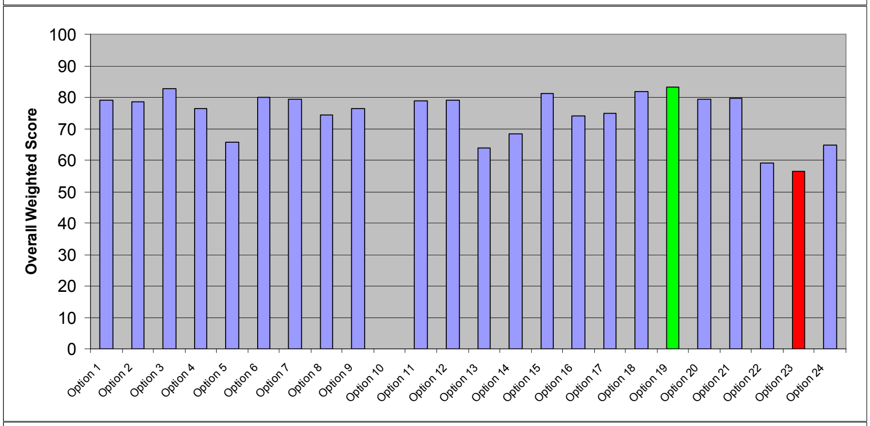
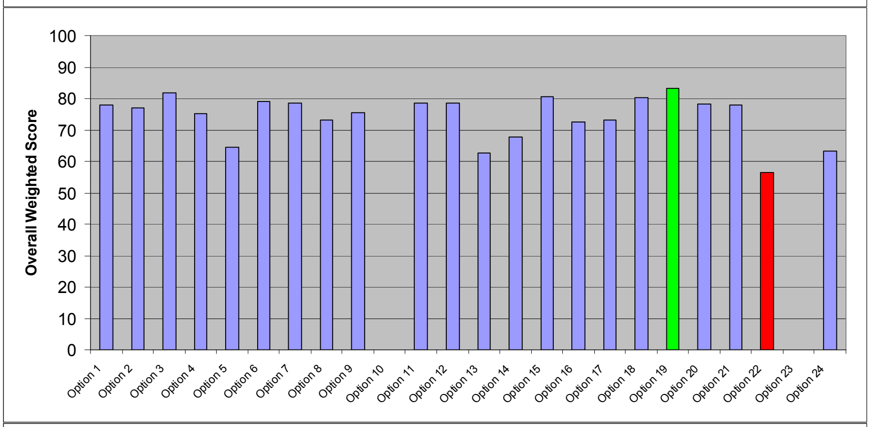
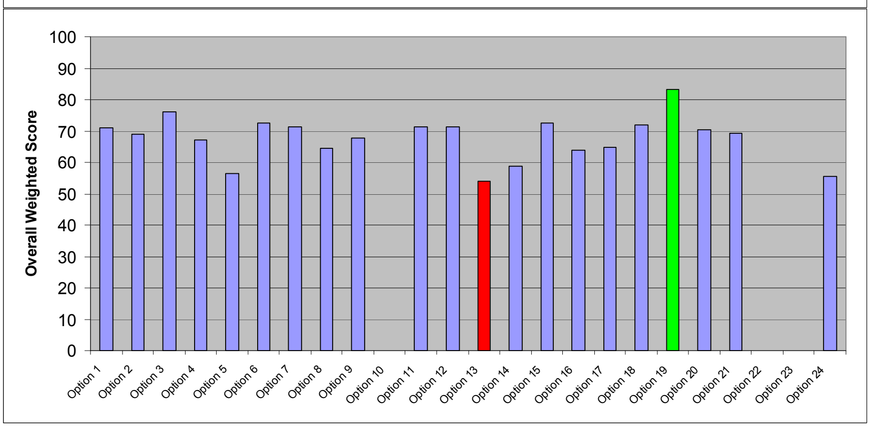
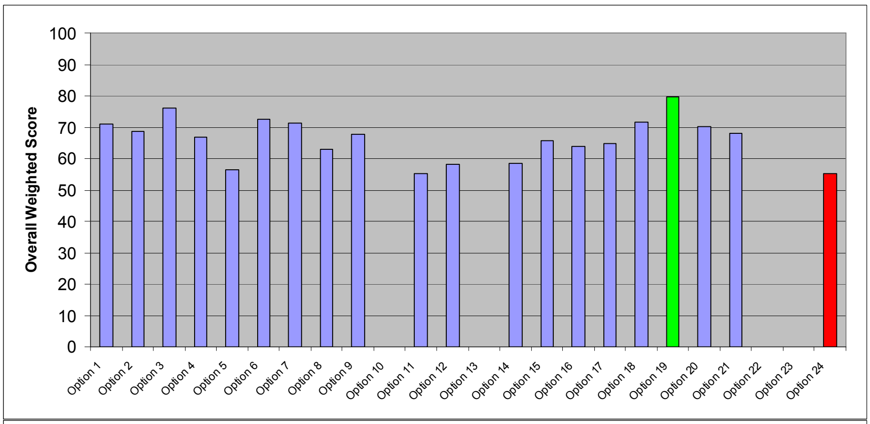
Appendix 3 – Allocation B – Narrow Weightings Results







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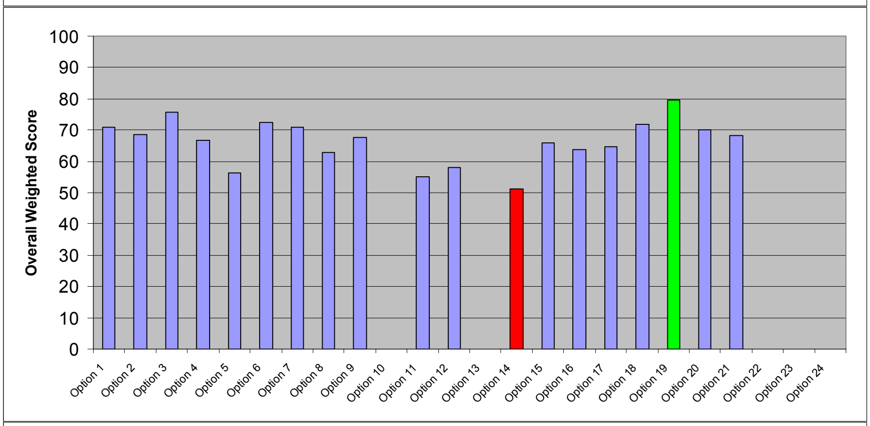
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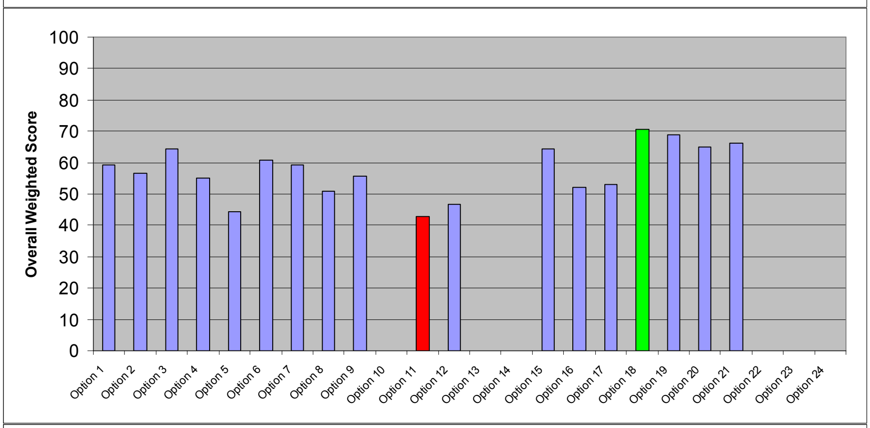
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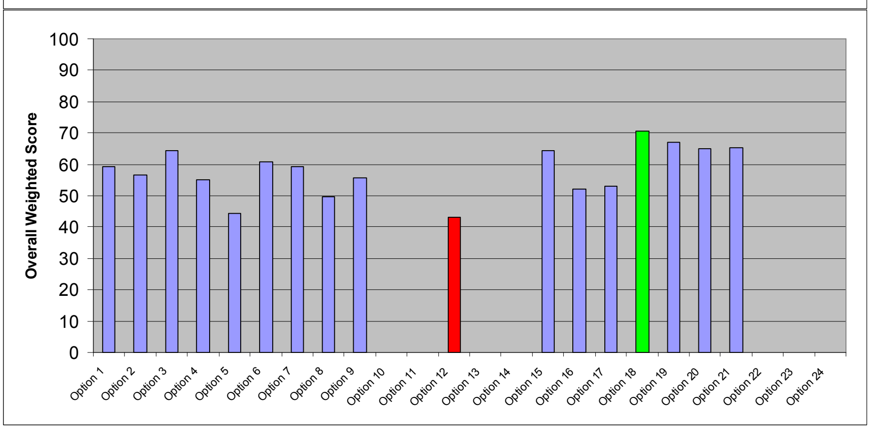
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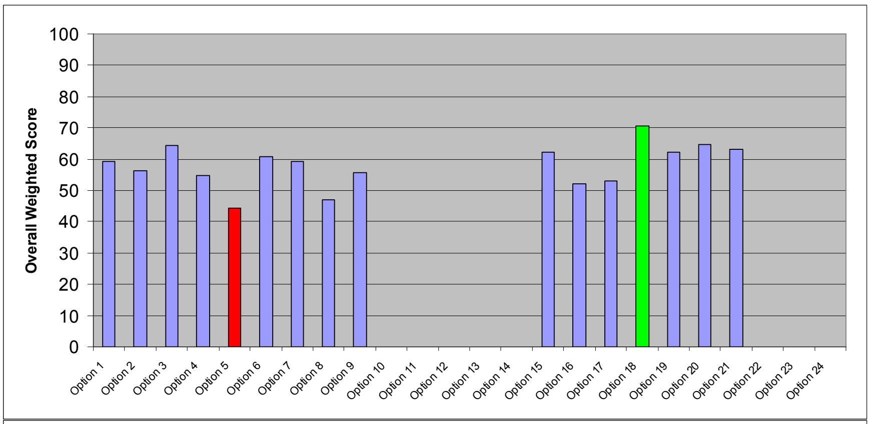
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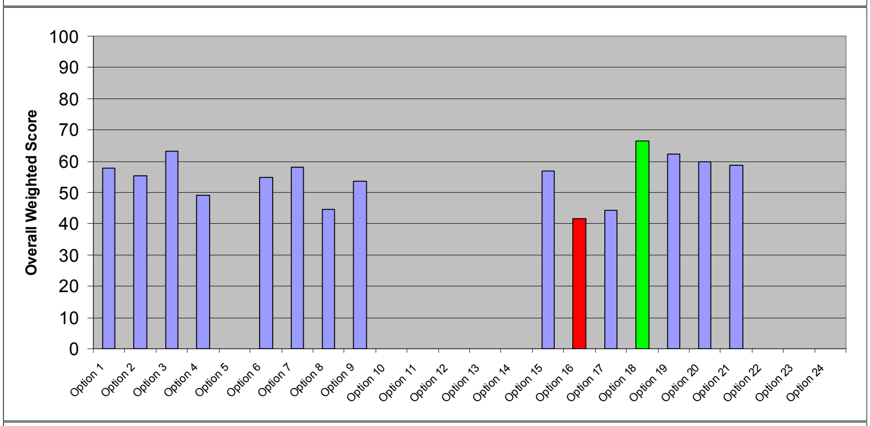
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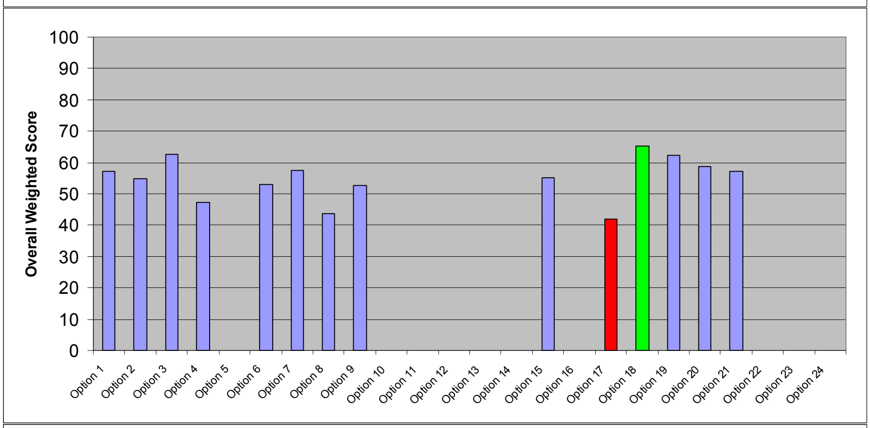
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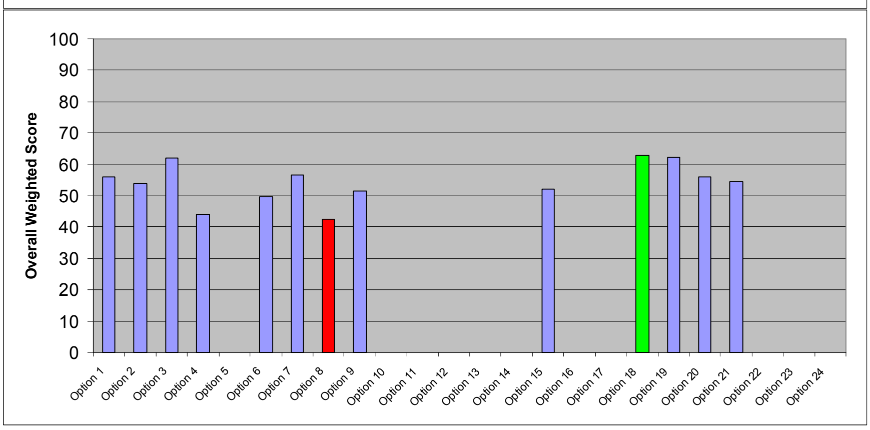
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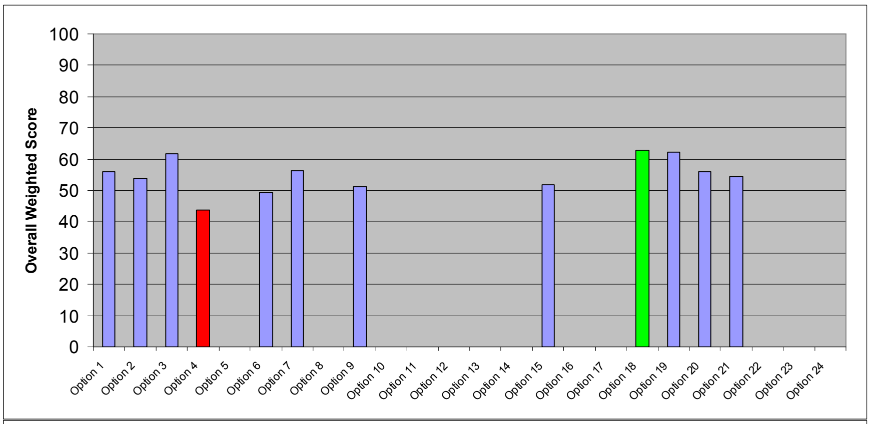
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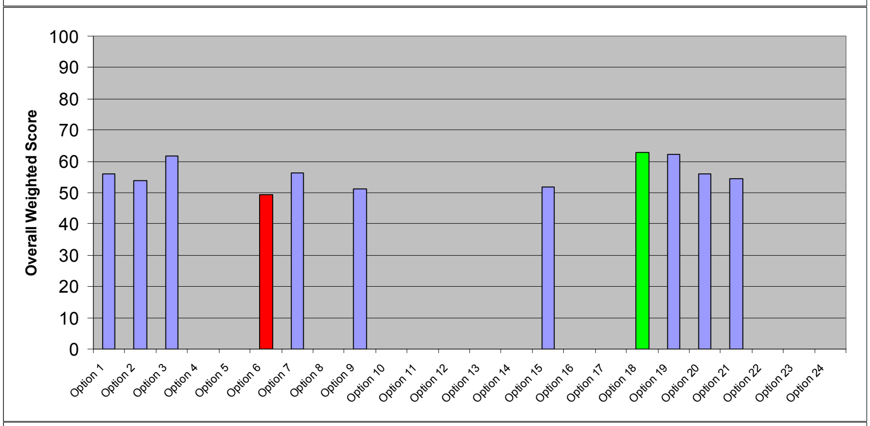
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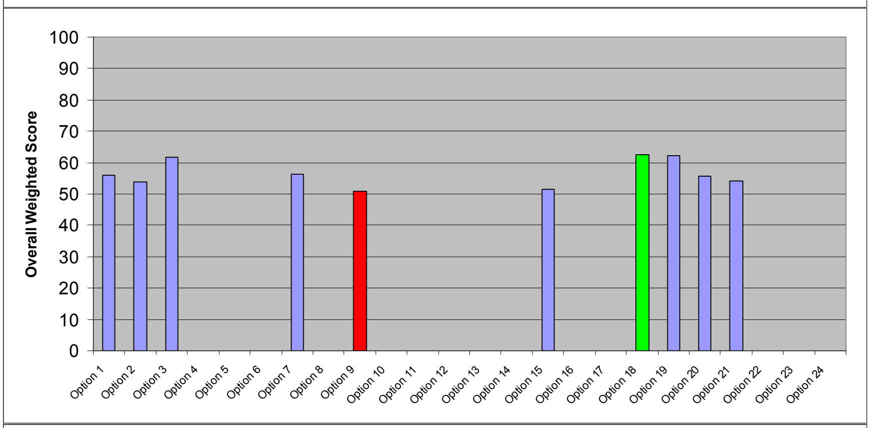
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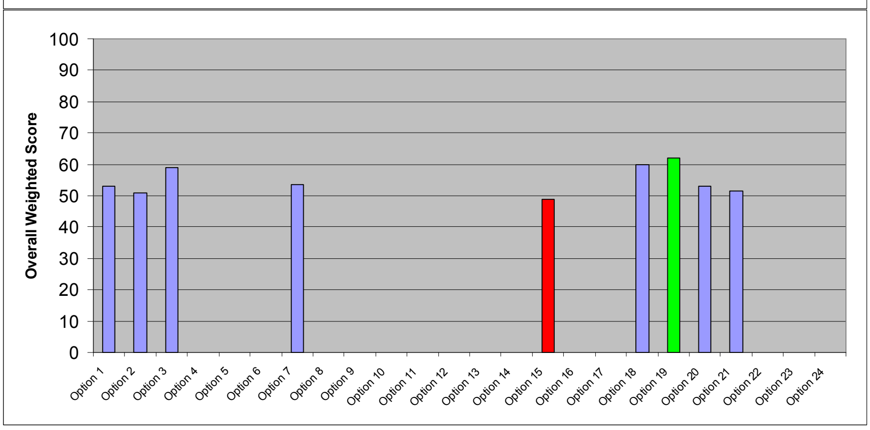
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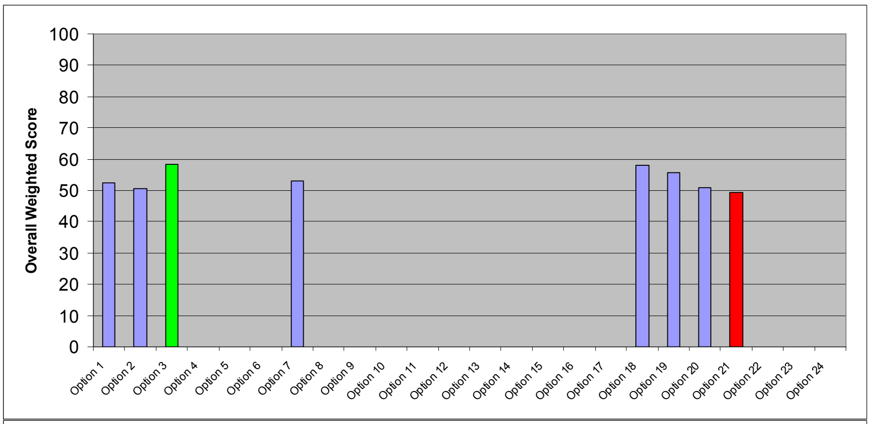
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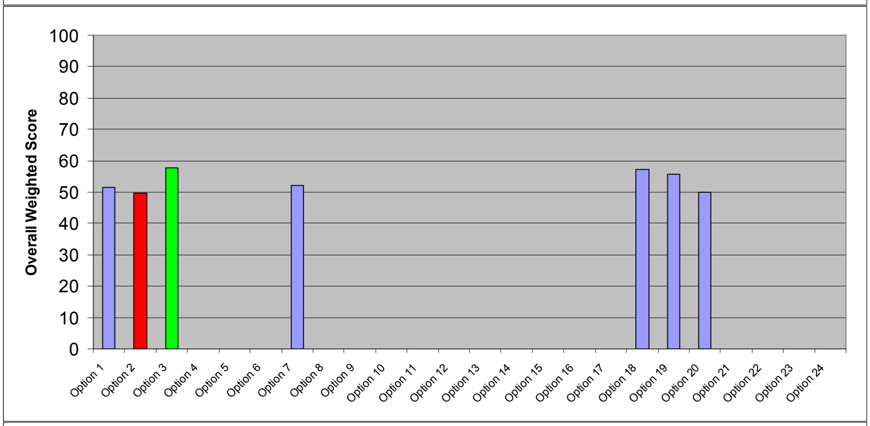
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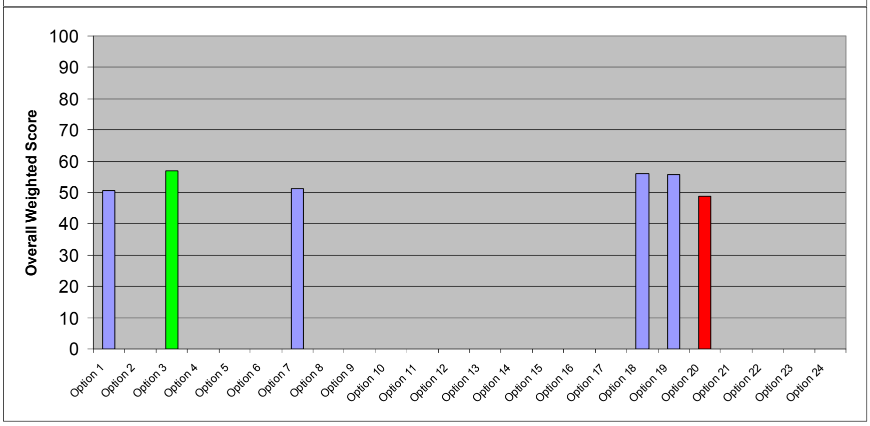
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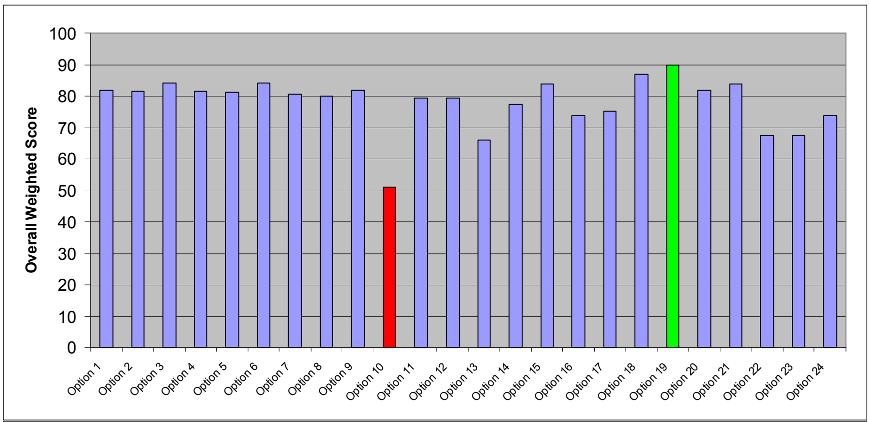
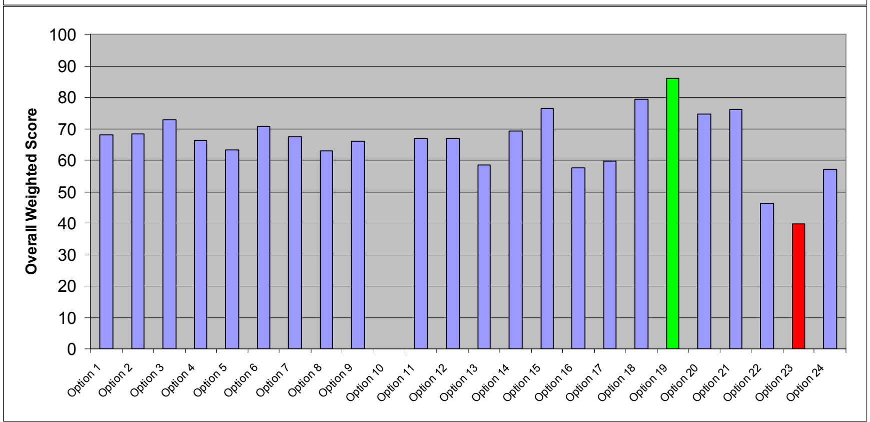
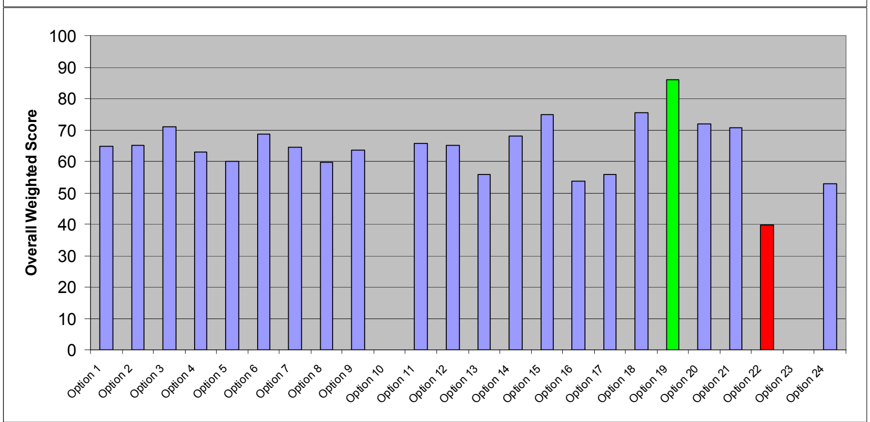
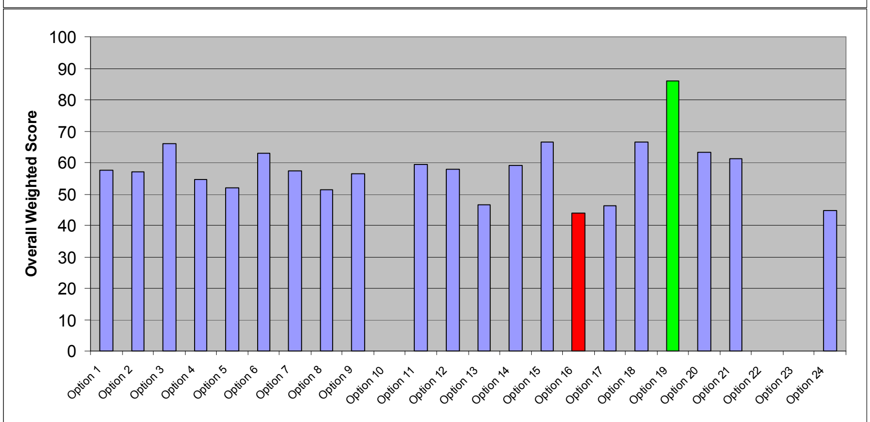
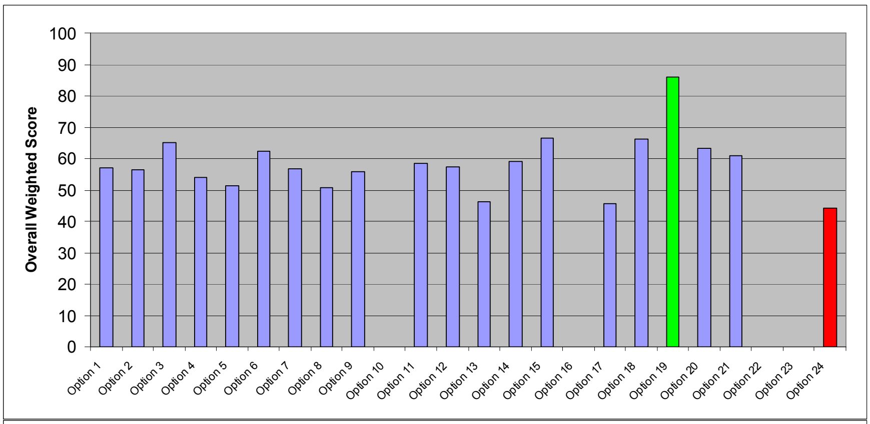
Appendix 4 – Allocation C – Narrow Weightings Results







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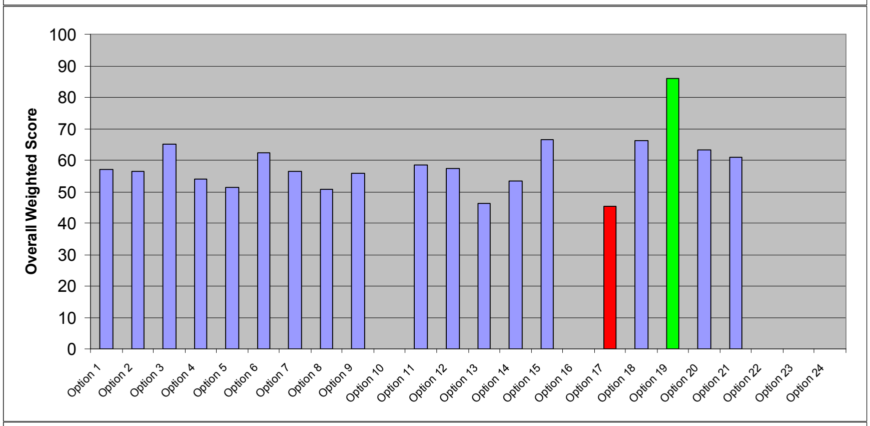
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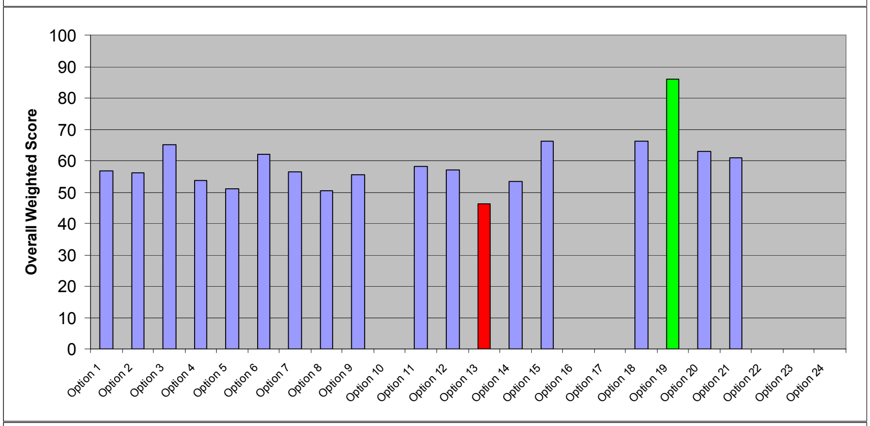
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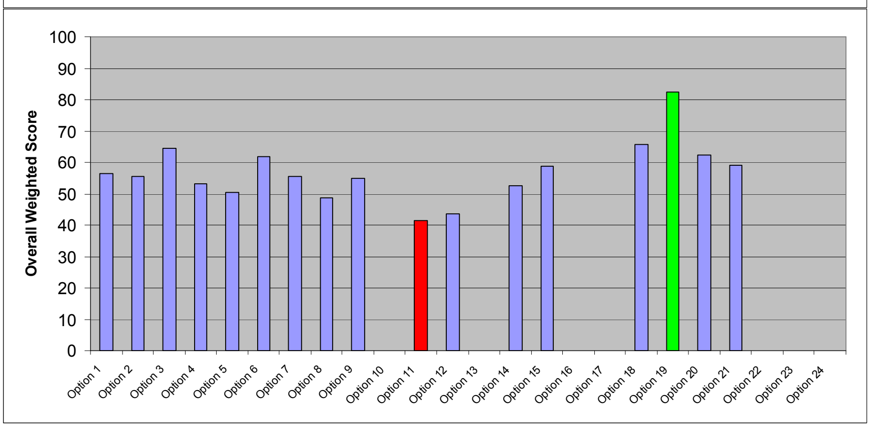
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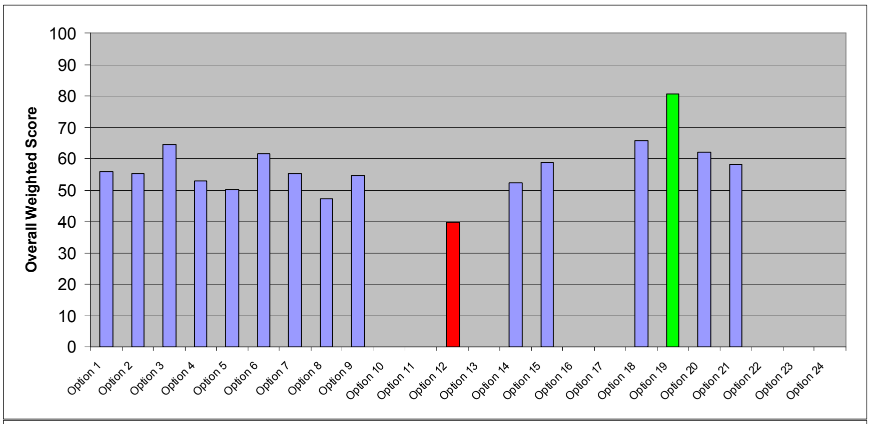
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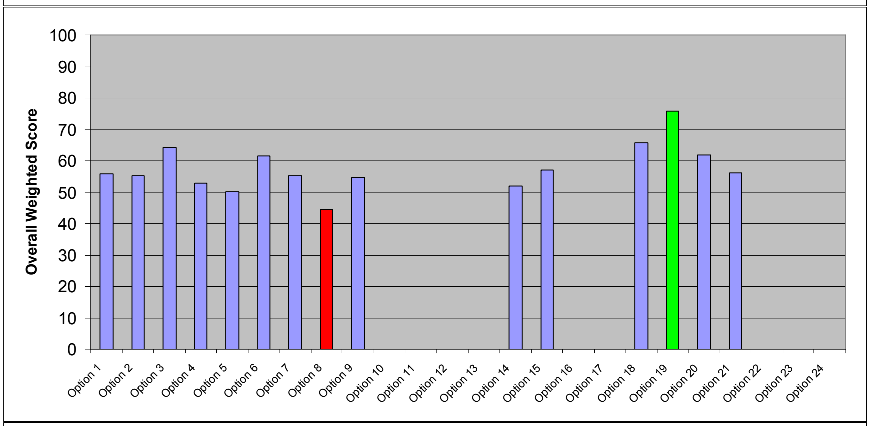
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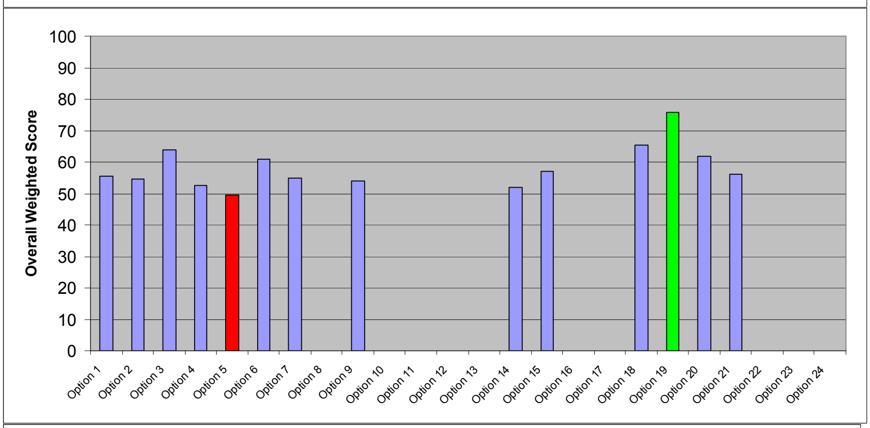
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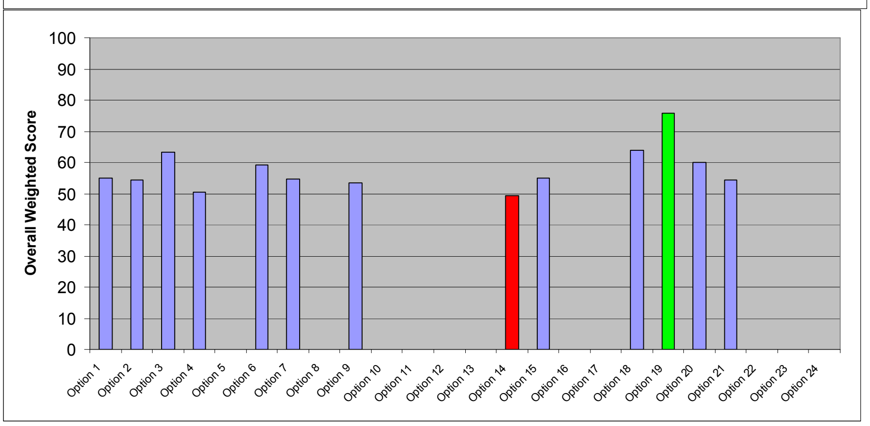
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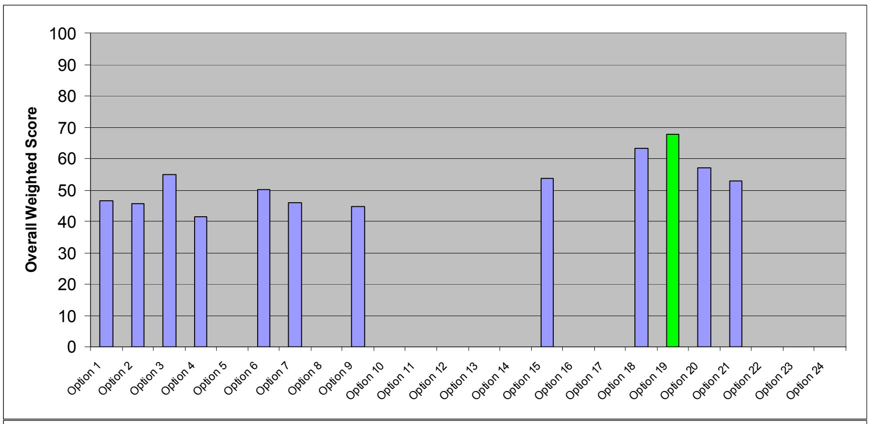
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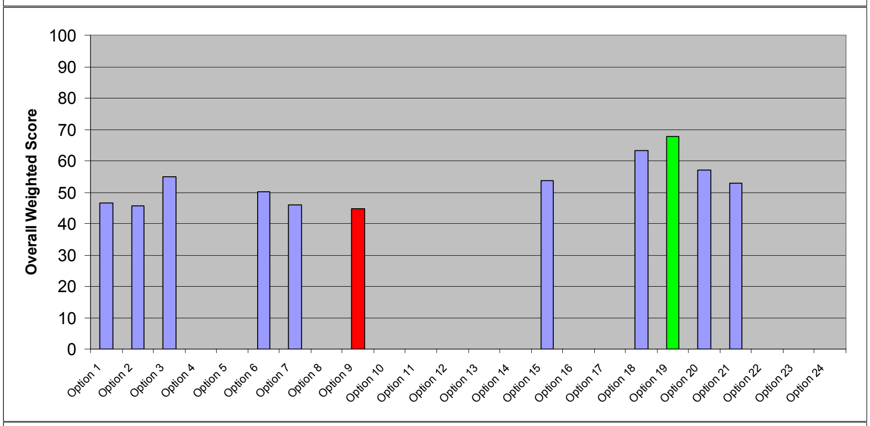
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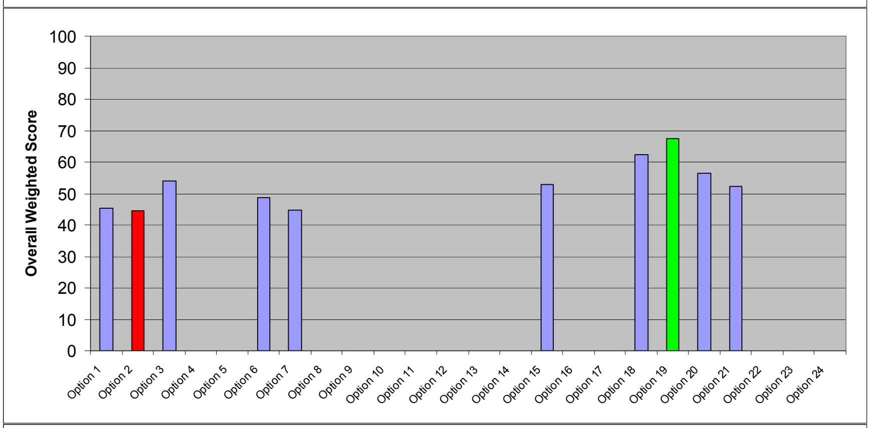
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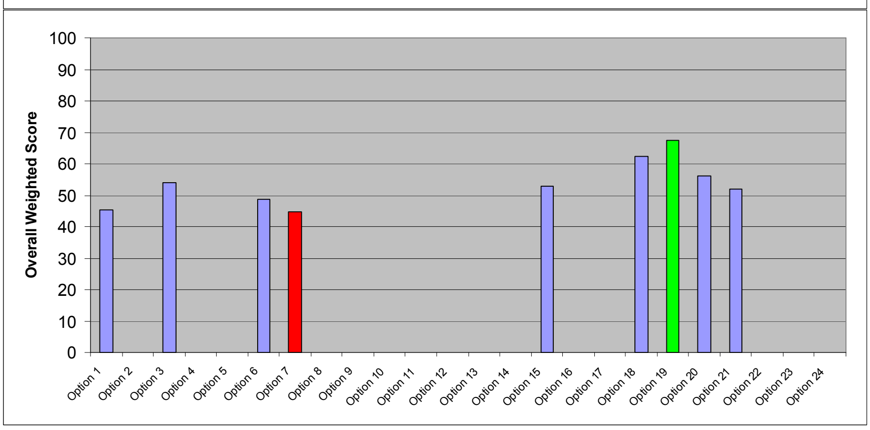
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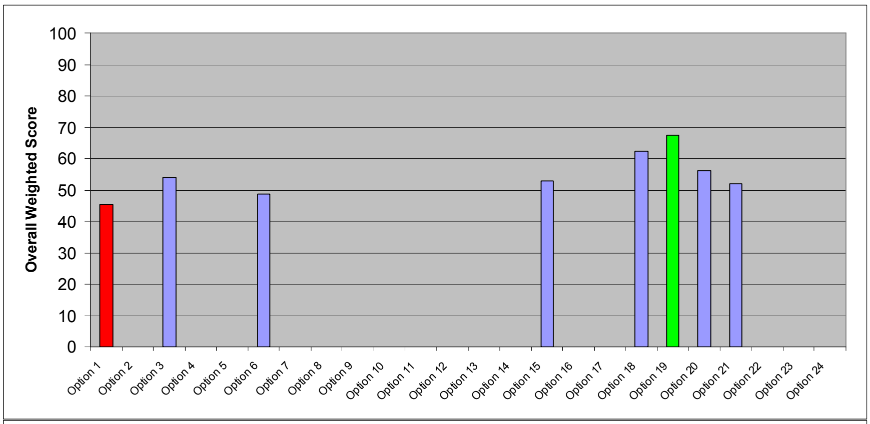
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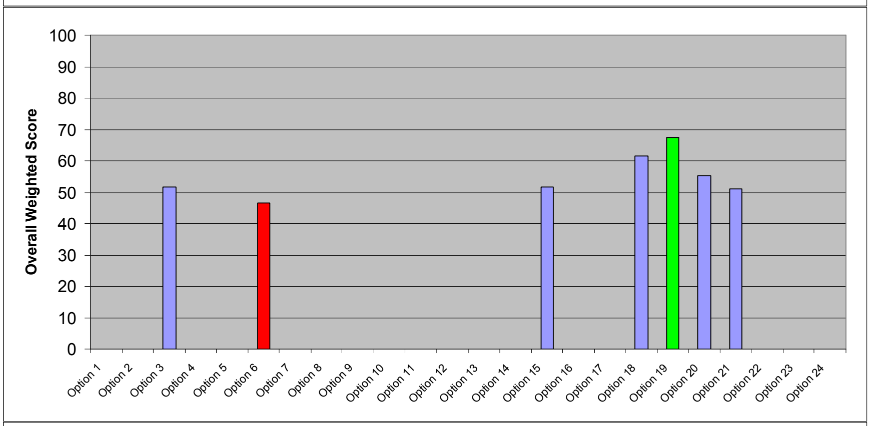
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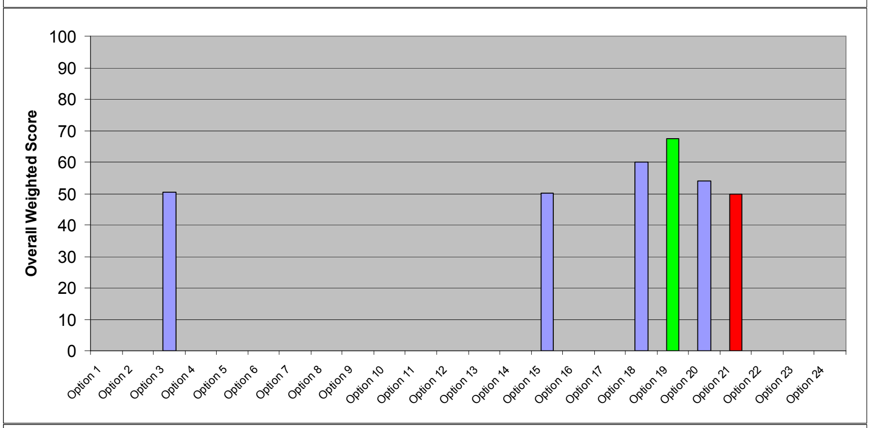
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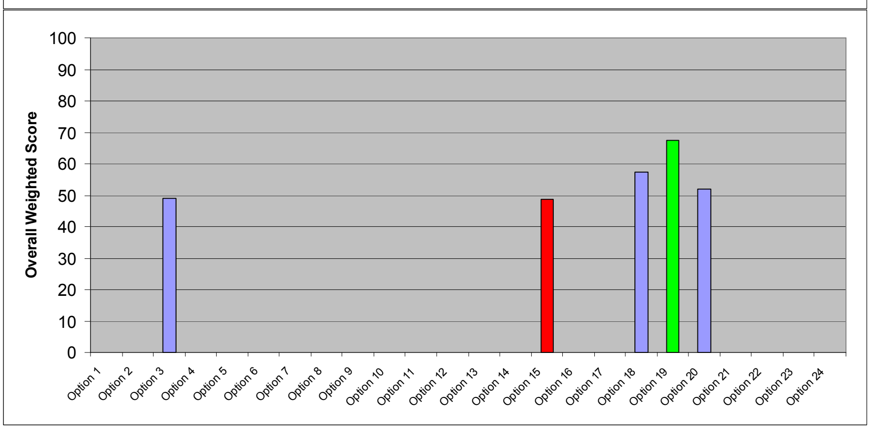
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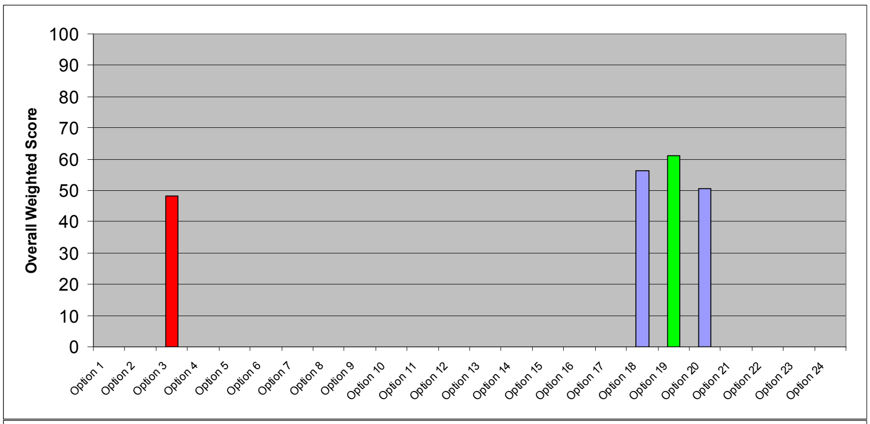
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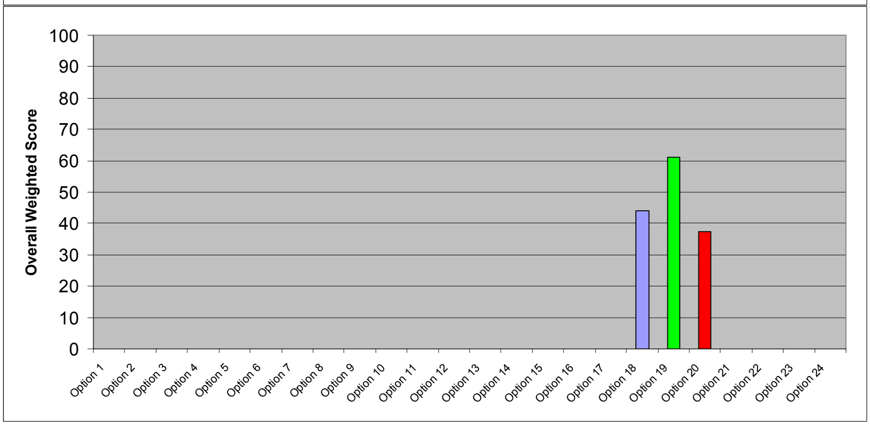
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Appendix 5 – In-situ Entombment Concept

Throughout the MCDA assessment, Option 19 (In-situ entombment) scores well. In the initial assessment it is the best performing option. In a variant case of Option 19, which considers a 1,000 year monitoring and maintenance period, this option scores less well, but is still amongst the best performing options.

Options that score well in this assessment of all twenty four CARBOWASTE options may not be acceptable to all (or any) partner countries; they have been determined in order to provide a fully representative set of options. Each partner country must make its own assessment as to the acceptability of any particular option.

This appendix provides a brief review of the entombment concept with consideration of its applicability to i-graphite.

The National Nuclear Laboratory (NNL) is preparing a position paper (NNL, in preparation) to review the strategic options for UK nuclear decommissioning, which considers ex-situ and in-situ (including immobilisation by entombment) decommissioning options for structures on nuclear sites.

In-situ decommissioning options can include:

- in-situ disposal of building structures with ex-situ disposal of inventory; and
- in-situ disposal of building structures with in-situ disposal of residual inventory.

It is possible that building structures would be partly removed for ex-situ disposal. The building could be capped and mounded over at full height, or the height may be reduced (partial demolition / demolition to ground level).

Benefits

The principal safety benefits to be gained from in-situ entombment are from significantly reduced radioactive waste handling activities. This would be offset by the need to remove higher activity / longer-lived nuclides to an acceptable level to avoid the need for long term institutional control.

The approach could ensure that damaged or degraded facilities are isolated from the environment through the strengthening of structures, immobilising contaminants and the building of curtain walls and capping structures.

Existing Experience

The approach has been implemented on a number of structures at the US National Labs at Hanford, Idaho and Savannah River sites. Temporary entombment structures have been erected around acutely damaged reactors, such as those at Chernobyl and Fukushima, but the approach of long-term entombment has not been applied in practice to power reactors.

Practical Considerations

The inherent robustness of a structure is key to delivering a safety case for a long period of institutional control. It is unlikely the building will have been designed for this function and might require significant modification, with associated costs.

Stabilisation of the structure using infill and/or grouting voids is required to reduce the risk of spread of contamination. Some of this material could be sourced from other decommissioned buildings on the same site.

A period of ten half-lives may be used as an indicator of radioactive decay to 'insignificant' levels. However, a period of 300 years is towards the upper limit of the period which has been claimed for institutional control (Environment Agency, 2009). While this would be sufficient for ^{60}Co present in metal components associated with i-graphite (half-life ~ 5 years), for ^{14}C (half-life ~ 5,730 years) and ^{36}Cl (half-life ~ 300,000 years), this period is clearly insufficient for reducing activity to insignificant levels.

Siting

An important consideration is the long-term risk from flooding (associated with global warming) or coastal erosion at the site of an entombed structure. This will be particularly significant for facilities at coastal locations susceptible to rises in sea level.

This approach is unlikely to be favoured in urban locations due to the value of land and pressure to release land for unrestricted re-use.

Existing experience is limited to relatively large, isolated sites, considerable distances from local populations.

Power reactor sites often have a high density of facilities and the ongoing requirement for land at such sites could preclude in-situ disposal in some cases. As sites are gradually decommissioned, however, this ongoing requirement for land will decrease. Additionally, a high density of buildings around a reactor building may preclude the use of capping and mounding approaches due to surrounding structures.

Costs

Most studies focus on the experience of in-situ disposal at US National Labs Hanford, Idaho and Savannah River sites. Cost savings of between $5 million and $300 million per facility compared to complete structure and inventory removal have been identified. These cost savings are, however, broad estimates and further analysis is required. The costs of securing regulatory approval of safety cases could vary significantly from country to country.

Stakeholder Agreement

Stakeholder agreement to in-situ entombment could be difficult to obtain, since this approach could be interpreted as a failure to achieve site clearance. The perceived legacy of entombed waste may be seen as intolerable for local residents. In practice, this would need to be considered alongside the impacts of constructing treatment or other facilities in the same locality with the associated impacts of transport etc.

The visual impacts of an entombed structure could be significant, depending on the location and the extent to which building height has been reduced. Concerns may arise over perceived risks of malicious or accidental intrusion onto the site.

Conclusions

While there is some experience regarding entombment, or in-situ decommissioning, of legacy nuclear facilities in the United States, and as a temporary solution for acutely damaged reactors, the approach of long-term entombment has not been applied in practice to power reactors. As such, it is not a technically proven solution and would likely require significant technological development before a safety case could be demonstrated for its use in immobilising i-graphite in-situ.

A key aim of in-situ entombment is to provide a secure form of containment for a sufficient period of time that allows radioactive decay of the contained inventory to insignificant levels. While this may be achievable for the relatively short-lived ^{60}Co, the long half lives of ^{14}C and ^{36}Cl mean that levels of activity for these isotopes would not have decreased significantly over a period of time considered acceptable for institutional control.

References

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