Optioneering of Transportation Systems in Nuclear Facilities

Gonçalo Botelho Teixeira
goncalo.b.teixeira@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisboa, Portugal

November 2022

Abstract

The master thesis addressed in this extended abstract uses an analysis/selection method, the Optioneering Analytic Hierarchy Process (OAHP) to perform a comparative evaluation and determine not only the best option among the assessed transportation systems (TS) but also the best features that a transportation system should have in order to accomplish all the proposed tasks within a nuclear fusion industry scenario. In addition, participants with remote handling background experience were invited to fill out a survey that was developed to analyze their opinions and enable the development of an OAHP that is built based on the participants' inputs to the survey. Finally, taking inspiration from two already existing analysis/selection methods, the OAHP and the Sifting method, a new Hybrid Selection Method (HSM) is developed, which is also a tool for the selection of ex-vessel (TS). The achievements and possibilities of this new analysis/selection method, the HSM, are discussed based on its results and based on a comparison between the results of all three selection methods mentioned: the OAHP, the Sifting, and the HSM. The results obtained by these selection methods are mostly used to develop, analyze and compare such selection methods.

Keywords: Optioneering, Criteria Decision Making, Nuclear Facilities, Ex-Vessel Transportation Systems, Remote Handling

1. Introduction

In the current state of the world, where fossil energy is becoming scarce and renewable energy is not enough to suppress the global energy demand, the need for a more reliable source of energy is present. Nuclear fusion promises to be the solution, since it creates less radioactive material than fission and has a nearly unlimited fuel supply.

The European Consortium for the Development of Fusion Energy, is working on a demonstration power plant called DEMO [1], its purpose is to take fusion from a science-driven, lab-based exercise to an industry-driven and technology-driven programme. A key criterion for DEMO is the production of electricity, although not at the price and the quantities of commercial power plants.

The DEMO's reactor shall require supervision and maintenance operations that cannot be done by humans due to the high levels of radioactive contamination that makes it inaccessible. This creates the need to perform these operations remotely to ensure safety conditions for the workers. This is where the ex-vessel transportation systems come in, to remotely perform the transport operations of heavy and activated loads. Differently from the common industry scenarios, ex-vessel transportation in nuclear facilities will have to deal with adversities like residual magnetic fields and radioactive exposure [2] [3]. Therefore, unlike common industry robots, the ex-vessel transportation systems (TS) are heavily-shielded TS that carry out tasks that are far too dangerous for human crews or even other robots [4] [5] [6].

2. Assessment of Industry Solutions

In the nuclear industry, robots have a fundamental role in which they allow for a more efficient maintenance of the facility while also lowering the risks of possible work catastrophes and personnel injuries [7] [8]. The use of robots allows for the maintenance process to occur while the fusion reactor is still active, which would be impossible to do with human workers due to the extreme hazardous environment conditions. The development and innovation of robotic solutions in this area are very complicated and slow due to the necessity to comply with numerous safety regulations like the "as low as reasonably practicable" principle (ALARP) [9], which sets the requirements and conditions to determine the level attributed to a robot's Technology, System and Integration Readiness Level [10] [11]. If a robot does not have a high enough level on these scales it will not be approved for further development nor production. Therefore, most of the technological solutions available in today's industry are commercial off-the-shelf (COTS) technologies.

Even if certain levels of customization are required, it is still considerably easier to modify an already existing solution that has high readiness level than to develop and test a new solution from scratch. Most manufacturers provide options to adapt the original product into one that best suits the costumer's needs, which becomes a modified off-the-shelf (MOTS) product. Therefore, to perform remote maintenance of the tokamak facility, assessing the solutions used in industry is the starting point to select the best option.

2.1. Industry solutions

Due to the design of the reactor and the nature of the maintenance operations inside it [12][13], the ex-vessel operations of transportation are required to transport heavy loads ($>$ 100 tons) along the galleries. These operations of transportation can be planned, identified as nominal operations, or unexpected operations such as the ones required in case of recovery or rescue. There is a preference for ground vehicles [2] in order to avoid the risk of falling loads and to also free ceiling space for pipes/hardware installation. Therefore, the proposed solutions will mostly be based around ground vehicles.

2.2. Assessed Options

This subsection shows the TS that were selected as possible solutions for the transportation operations, also depicted in Figure 1.

- Pallet Transporters (PT) [14]
- Mobile Gantry Cranes (MGC) [15]
- Re-Sizable Multipurpose Vehicles (RSMV) [16]
- Indoor Self-Propelled Modular Transporters (ISPMT) [17]
- Tooling and Production Platforms (TPP) [18]
- Extra Low Production Line Platforms (ELPLP) [19]
- KUKA Omni Move AGV (KOMAGV) [20]
- KUKA Mobile Platform – 1500 (KMP) [21]
- Coil Transfer Cart (CTC) [22]
- Mecanum Wheel Omnidirectional Mobile Platform (MWOMP) [23]
- Shifter Trailer (ST) [24]
- Shifter Mono (SM) [25]
- Shifter Flex (SF) [26]
- Shifter Multi-flex (SMF) [27]


Pallet Transporters **(PT)**

Mobile Gantry Cranes **(MGC)**

Re-Sizable Multipurpose vehicles **(RSMV)**

Indoor Self-Propelled Modular Transporters **(ISPMT)**

Tooling and Production Platforms **(TPP)**

Extra low production line platforms **(ELPLP)**

KUKA omni Move AGV **(KOMAGV)**

KUKA Mobile Platform 1500 **(KMP)**

Coil Transfer Cart **(CTC)**

Mecanum wheel omnidirectiona mobile platform **(MWOMP)**

shifter Trailer **(ST)**

shifter Mono **(SM)**

shifter Flex **(SF)**

shifter multi-Flex **(SMF)**

Figure 1: Assessed Transportation Systems

2.3. Evaluation Criteria

Different solutions are available to accomplish the requirements of the ex-vessel transportation in DEMO [28]. Some of them are already applied in industry, while others are from the prototypes emerging in laboratories to the ones almost reaching the last TRL. This section presents evaluation criteria to rank the possible solutions for the lifetime of DEMO. The evaluation criteria are specifically based on technological features of mobile robots to address the transportation systems.

- **Technical Feasibility (A):** The ex-vessel TS need to operate autonomously under human supervision. In case of failure, the remote control should be taken over by human intervention. The next sub-criteria relate to guidance, navigation, and control: Maneuverability [29], Size [29], Accessibility, Speed, Stability, Collisions [30], Payload, Flexibility, Accuracy, Time Response, Power Supply, Communications, Multi Operations

- **Robustness (B):** These sub-criteria relate to how well a vehicle can withstand physical and radiation damage over time without compromising its ability to perform transportation operations: Radiation Impact, Operation Environment, Sensor Redundancy, Physical Robustness and Frame Integrity, Integrity Checking

- **Costs (C):** These sub-criteria refer to financial, operation, infrastructural, and time costs: CAPEX on Environment, OPEX on Environment, CAPEX on Equipment/Hardware, OPEX on Equipment/Hardware, Readiness Level Cost Impact, Bespoke Systems Cost Impact

- **Replacement Ability (D):** These sub-criteria relate to how easily the technologies/equipment of a TS can be replaced, taking into consideration market availability, lifetime expectations, and physical replacement of those technologies: Technology Maturity, Sustainability, Replacement Difficulty, Replacement Frequency, Equipment Complexity

- **Recovery and Rescue (E):** In the case a nominal operation is interrupted, either the operation can be resumed from where it ended, or another nominal operation will need to be initiated. If not possible a rescue/recovery operation is required. These sub-criteria relate to the performance and frequency of such operations: Risk of Failure, Ability to Fail-Safe, Dependency

2.4. Multiple-Criteria Decision Making/Analysis

To select the best option, a selection method needs to be defined. There are different selection methods based Multiple-Criteria Decision Analysis (MCDA) [31], such as the optioneering [32] or the sifting [33]. The optioneering embraces, by itself, multiple methods such as the Analytic Hierarchy Process (AHP) [32]. For this study, a transportation solution will be selected using one of the MCDA methods assessed bellow:

- **Optioneering AHP:** Makes use of pairwise comparisons between different features, solutions, or criteria and establishes a qualitative measure of the relation between them (how much more important is one in relation to another) using a quantitative representation, allowing for the ranking of the proposed options.

- **Sifting:** This method is most adequate for cases where the final product's concept is already envisioned. This method works by sifting a large number of options until only one or a few of them remain. The sifting process is made by criteria/feature checking, allowing for options that have the highest number of required features to advance to the next sifting phase while others are discarded.

- **Points system:** This method uses point values to determine the best option among all. A point value for each level on a criterion represents the combined effect of the criterion's relative importance (weight) and its degree of achievement as reflected by the level (level being the qualitative measure from poor to excellent).

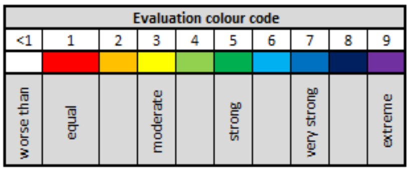
- **Bisection method:** In this method, for each determined criterion, the lowest and highest performing alternatives are identified and rated 0 and 100 respectively. The performance on the criterion that is halfway between the two extremes is, therefore, worth 50 (midway between 0 and 100) and is defined. The next two midpoints on the criterion relative to the performances worth 0 and 50 and 50 and 100 respectively are then defined. These two endpoints and three midpoints are usually sufficient to trace out the approximate shape of the criterion's 'value function'.

Considering all the previous methods, the optioneering AHP is the most viable candidate since it uses a good balance between subjective inputs and objective weighting to score and rank the options. The sifting methodology requires a more explicit knowledge about the required features for the final transportation solution, which is not achievable at this stage. The point system uses a qualitative assessment through the attribution of points like the optioneering but does not present any level of comparison between options, evaluating only their performance in terms of criteria efficiency. The Bisection method is not as flexible and detailed as the optioneering AHP and the sifting, since it eliminates the possibility of scoring options close to each other, allowing only for them to rank exactly in between other options.

3. Optioneering Applied to Transportation Systems

3.1. Optioneering

To perform the selection and evaluation of the transportation systems mentioned in Section 2.4, the Optioneering AHP (OAHP) was chosen. The OAHP relies on multiple matrices [34] that contain pairwise comparisons between criteria and also between TS options. The pairwise comparison matrices use a colour code seen in Figure 2 to translate a qualitative relation between two options within the comparison matrix.



Evaluation colour code									
<1	1	2	3	4	5	6	7	8	9
⬜	🟥	🟧	🟨	🟩	🟩	🟦	🟦	🟦	🟪
worse than	equal		moderate		strong		very strong		extreme

Figure 2: Colour code for qualitative comparison

By determining the weights of each row of the OAHP comparison matrices, a final evaluation table can be assembled, which will allow for the ranking of every single transportation system that was considered in Section 2. These matrices represent a relation that can be answered by the question: “how much better is the feature on the left compared with the feature on the top of the matrix?”. The answer to this question is displayed in the element of the matrix that intersects the desired row and column, following the metrics introduced in figure 2. The last column named “Wt.” represents the computed weights for each row of the matrix, and on the bottom left corner of each table, it is shown the Consistency Ratio (CR) between the values of the table. These comparison matrix characteristics can be seen in Figure 3.

The weights are obtained by the principal eigenvector method. The principal eigenvector is the vector V that corresponds to the largest eigenvalue λ_{max} of matrix M, such that the following equation holds:

$$Av = \lambda_{max} v \tag{1}$$

A vector $W = [w_i]$ representing the weights is then obtained by normalizing $V = [v_i]$

$$w_i = \frac{v_i}{\sum_i v_i} \tag{2}$$

The OAHP allows for some inconsistency in judgements when doing pairwise comparisons (eg.: if A is better than B and B is better than C, A should be better than C to maintain good consistency). To measure the level of inconsistency, the consistency index (CI) and consistency ratio (CR) are used. If matrix M of order n is absolutely consistent, the largest eigenvalue λ_{max} is equal to n. The CI measures the difference of λ_{max} from this ideal value.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

The CR compares the CI to the average of the same parameter, RI, which is obtained from a large number of random matrices.

$$CR = \frac{CI}{RI} \tag{4}$$

The values for RI can be found in precalculated tables in the literature, see for example Table 1. An acceptable consistency ratio should be about 10% or less, otherwise the consistency should be improved [31].

Table 1: Average consistency indexes RI of random matrices [35]

n	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.5247	0.8816	1.1086	1.2479	1.3417	1.4057	1.4499	1.4854	1.5140	1.5365	1.5551	1.5713	1.5838

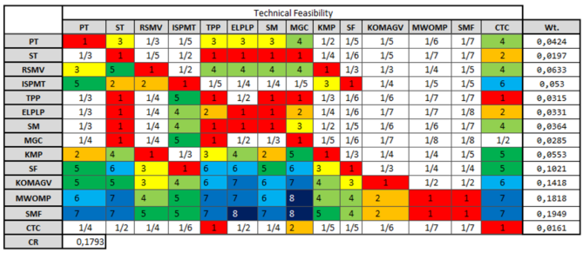
4. Comparison Matrices

4.1. Transportation Systems Comparison Matrices

The transportation systems comparison matrices display the comparison between all assessed TS when compared under one specific group of criteria, which was identified in Section 2.3. These comparisons are made using the metrics detailed on Figure 2.

All the transportation systems comparison matrices can be found in the master thesis document. As an example, Figure 3 shows the pairwise comparison matrix between every assessed TS. This comparison is made in terms of Technical Feasibility criteria.

Figure 3 shows that the TS with the best performance under the Technical Feasibility criterion are the SMF, the MWOMP and the KOMAGV, which all present high freedom of maneuvering, an already implemented and tested navigation and guidance system and the ability to deal with the weight of the transported loads. The major downside of KOMAGV and MWOMP is their size, these two also present a relevant elevation capability. The SMF as a more reduced size and can operate cooperatively with other SMF transportation systems,



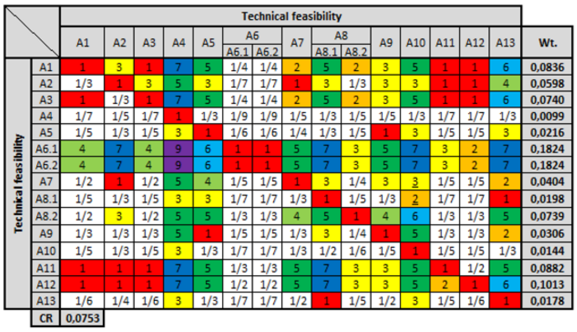
	Technical Feasibility														
	PT	ST	RSMV	ISPMT	TPP	ELPLP	SM	MGC	KMP	SF	KOMAGV	MWOMP	SMF	CTC	Wt.
PT	1	3	1/3	1/5	3	3	3	4	1/2	1/5	1/5	1/6	1/7	4	0,0424
ST	1/3	1	1/5	1/2	1	1	1	1	1/4	1/6	1/5	1/7	1/7	2	0,0197
RSMV	3	5	1	1/2	4	4	4	4	1	1/3	1/3	1/4	1/5	4	0,0633
ISPMT	5	2	2	1	1/5	1/4	1/4	1/5	3	1	1/4	1/5	1/5	6	0,053
TPP	1/3	1	1/4	5	1	1/2	1	1	1/3	1/6	1/6	1/7	1/7	1	0,0315
ELPLP	1/3	1	1/4	4	2	1	1	2	1/4	1/6	1/7	1/7	1/8	2	0,0331
SM	1/3	1	1/4	4	1	1	1	3	1/2	1/5	1/6	1/6	1/7	4	0,0364
MGC	1/4	1	1/4	5	1	1/2	1/3	1	1/5	1/6	1/7	1/8	1/8	1/2	0,0285
KMP	2	4	1	1/3	3	4	2	5	1	1/3	1/4	1/4	1/5	5	0,0553
SF	5	6	3	1	6	6	5	6	3	1	1/3	1/4	1/4	5	0,1021
KOMAGV	5	5	3	4	6	7	6	7	4	3	1	1/2	1/2	6	0,1418
MWOMP	6	7	4	5	7	7	6	8	4	4	2	1	1	7	0,1818
SMF	7	7	5	5	7	8	7	8	5	4	2	1	1	7	0,1949
CTC	1/4	1/2	1/4	1/6	1	1/2	1/4	2	1/5	1/5	1/6	1/7	1/7	1	0,0161
CR	0,1793														

Figure 3: Technical Feasibility comparison matrix regarding Transportation Systems

which makes it an adequate TS to transport casks using a pallet structure.

4.2. Evaluation Criteria Comparison Matrices

Evaluation criteria comparison matrices translate pairwise comparisons between different grouped criteria, answering the question: "how much better is the sub-criterion on the left compared with the sub-criterion on the top of the matrix". For example, Figure 4 depicts the pairwise comparisons between all the sub-criteria of the Technical Feasibility criterion. Once again, these sub-criteria are introduced in section 2.3.



		Technical feasibility															
		A1	A2	A3	A4	A5	A6		A7	A8		A9	A10	A11	A12	A13	Wt.
							A6.1	A6.2		A8.1	A8.2						
Technical feasibility	A1	1	3	1	7	5	1/4	1/4	2	5	2	3	5	1	1	6	0,0836
	A2	1/3	1	3	5	3	1/7	1/7	1	3	1/3	3	3	1	1	4	0,0598
	A3	1	1/3	1	7	5	1/4	1/4	2	5	2	3	5	1	1	6	0,0740
	A4	1/7	1/5	1/7	1	1/3	1/9	1/9	1/5	1/3	1/5	1/5	1/3	1/7	1/7	1/3	0,0099
	A5	1/5	1/3	1/5	3	1	1/6	1/6	1/4	1/3	1/5	1	3	1/5	1/5	3	0,0216
	A6.1	4	7	4	9	6	1	1	5	7	3	5	7	3	2	7	0,1824
	A6.2	4	7	4	9	6	1	1	5	7	3	5	7	3	2	7	0,1824
	A7	1/2	1	1/2	5	4	1/5	1/5	1	3	1/4	3	3	1/5	1/5	2	0,0404
	A8.1	1/5	1/3	1/5	3	3	1/7	1/7	1/3	1	1/5	1/3	2	1/7	1/7	1	0,0198
	A8.2	1/2	3	1/2	5	5	1/3	1/3	4	5	1	4	6	1/3	1/3	5	0,0739
	A9	1/3	1/3	1/3	5	1	1/5	1/5	1/3	3	1/4	1	5	1/3	1/3	2	0,0306
	A10	1/5	1/3	1/5	3	1/3	1/7	1/7	1/3	1/2	1/6	1/5	1	1/5	1/5	1/3	0,0144
	A11	1	1	1	7	5	1/3	1/3	5	7	3	3	5	1	1/2	5	0,0882
	A12	1	1	1	7	5	1/2	1/2	5	7	3	3	5	2	1	6	0,1013
	A13	1/6	1/4	1/6	3	1/3	1/7	1/7	1/2	1	1/5	1/2	3	1/5	1/6	1	0,0178
	CR	0,0753															

Figure 4: Technical Feasibility comparison matrix regarding evaluation criteria

Analyzing the matrix in Figure 4, by comparing the relative importance of all the sub-criteria that belong to the technical feasibility criterion, it shows that A6.1 (collision avoidance) and A6.2 (collision detection) are the most relevant criteria, this is understandable when considering that giving more relevance to collision related criteria helps to lower the risks during nominal operations. A12 (Communications) was also attributed a high weight value, giving more relevance to the communications between the TS and other entities (control room, other TS and other components). The A4 (Speed) was the lowest ranked criterion out of the technical feasibility group, although it is an important criterion, control and precision of the TS movements are more important than locomotion speed.

Due to the nature of all of the evaluation criteria, their pairwise comparison becomes more difficult to assess. This means that even though some criteria are more important than others, they are not dominantly more important.

4.3. Final Evaluation of the Transportation Systems

After obtaining and analyzing all the required comparison matrices, the next step is to compute the final evaluation scores of all the assessed TS, that will allow for their ranking. To get the final scores, the obtained weights of the individual TS calculated as depicted in Section 4.1 are multiplied by the weights of each individual evaluation criterion obtained as shown in Section 4.2 and then the values are added.

$$TS_{sc_i} = Wt_{sc_i} \, . \, Wt_{TS} \tag{5}$$

$$TS_{c_j} = \sum TS_{sc_i} \tag{6}$$

$$TS_{fs_k} = \sum TS_{c_j} \tag{7}$$

Where sub-criterion score (sc in TS_{sc_i}) refers to the sub-criterion group scores, like A1, A2, A3, ... and the criterion score (c in TS_{c_i}) refers to the criterion major group scores like A, B, C, D and E, which are given by the sum of their sub-criterion scores. Wt_{sc_i} is the weight computed for the respective sub-criterion group, which the values are displayed on the far-right column of the evaluation criteria comparison matrices of Section 4.2, labeled as Wt. Wt_{TS} is the weight computed for the respective TS. Finally the TS_{fs}, where fs stands for final score, is the score attributed to a TS at the end of the evaluation from which they are ranked.

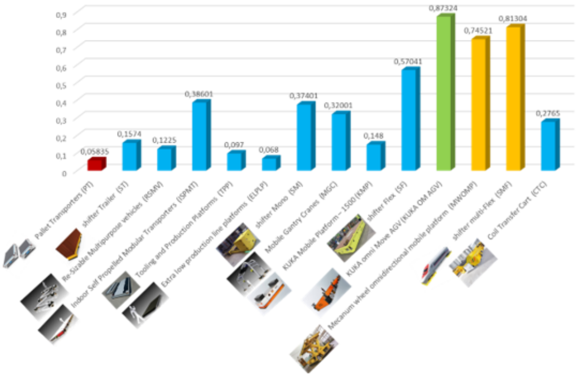


Figure 5: Final evaluation score for the assessed transportation systems.

Figure 5 shows that, the TS with highest score is the KOMAGV. The TS with the worst score were the PT and KMP. It is also worth considering the MWOMP and the SMF. Both of them ranked high among the other options and seem to have fitting characteristics/features to be selected as ex-vessel TS, like: Pallet transportation design, high capability for tandem operations, adequate payload capacity (> 100 tons alone or in tandem), omnidirectional locomotion due to the use of Mecanum Omni wheels.

In the OAHP methodology it is important to note that the results are dependent of the quality of the data used. In the OAHP case, data refers to the content of the comparison matrices that represent the qualitative comparison between options, and quality of the data refers to the consistency of the values and how accurately those values represent reality. The OAHP data can be improved as follows:

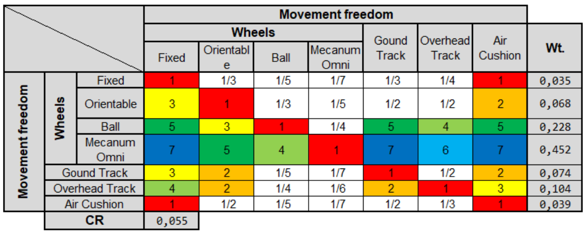
1. More comparison matrices must be achieved, mainly the comparisons between possible features for the transportation robots. Thus, the features can be treated as building blocks and, at the end, a TS is designed with a combination of the best features for the operations in the target scenario of DEMO.
2. The reliability of the data in the comparison matrices must be improved. The comparison matrices rely solely on the experience of the individuals performing the assessment, in this case the author of this document. Therefore, a survey should be done with a group of participants with background experience in remote handling. Such survey will provide the means to build an additional data representation of the OAHP comparison matrices.

4.4. Feature Analysis Comparison Matrices

Unlike transportation systems and evaluation criteria comparison matrices, feature analysis comparison matrices are not a required input for the development of the OAHP. The main purpose of these comparison matrices is to provide some level of insight into what individual features of TS are the most adequate to be used within the nuclear fusion industry scenario.

The features of the TS will be divided into several groups, movement freedom, sensors, power sources, safety systems, communications (type and frequency of communications), control, and guidance. Their evaluation matrices will have the same metrics (color-coded) as the ones presented in Figure 2.

The movement freedom feature can be used as an example of a feature analysis comparison matrix. It concerns the type of wheels/locomotion device used by the TS. It is directly responsible for its degree of accessibility. Hence, wheels that allow for a higher degree of freedom/accessibility are given higher importance when compared with other types of wheels. Observing the matrix in Figure 6, the Mecanum Omni wheel presented the best score when compared with the others. Although Mecanum wheels are usually larger and heavier, the choice is understandable since they can perform movements in any direction without needing to rotate the frame of the TS.



			Movement freedom							
			Wheels							
			Fixed	Orientable	Ball	Mecanum Omni	Gound Track	Overhead Track	Air Cushion	Wt.
Movement freedom	Wheels	Fixed	1	1/3	1/5	1/7	1/3	1/4	1	0,035
		Orientable	3	1	1/3	1/5	1/2	1/2	2	0,068
		Ball	5	3	1	1/4	5	4	5	0,228
		Mecanum Omni	7	5	4	1	7	6	7	0,452
	Gound Track		3	2	1/5	1/7	1	1/2	2	0,074
	Overhead Track		4	2	1/4	1/6	2	1	3	0,104
	Air Cushion		1	1/2	1/5	1/7	1/2	1/3	1	0,039
	CR		0,055							

Figure 6: Movement freedom comparison matrix

4.5. Results Analysis

For the ex-vessel transportation system to perform the expected transportation, several sub-systems need to be implemented. It is required to either select an already existing TS that will carry the cask or to design a TS (around an existing solution or from scratch). Selecting a solution that is already available in the market is more cost-efficient. On the other hand, designing a TS is more likely to be an optimal solution, but more expensive. The use of the OAHP to perform the selection of a TS resulted in the ranking of the assessed options, and an understanding that the baseline of an ideal TS that operates under the nuclear fusion scenario possesses the following features: Mecanum Omni Wheel for maneuvering purposes, Laser sensors for perception of the environment, Power supply system consisting of an on-board battery, Locking systems, anti-tilting and sliding mechanisms that allow for secure exchange operations, Full-time wireless communications, Semi-automated guidance control, and Laser contour for guidance.

5. Survey Analysis/ Data Validation and Improvement

Taking into consideration that most of the OAHP comparison tables were filled with data that represented the knowledge and point of view of a single person, a survey was developed and delivered to several specialists of related areas, with the intention to compare and improve the OAHP results based on the surveyed people's knowledge and experience. The surveyed individuals were invited to fill the survey and willingly accepted to do so. The collected data from the survey was then migrated to an Excel file for analysis and development (A&D) purposes.

5.1. Survey Implementation and Functioning

Every question in the survey asks the participants to score from 1 to 9 multiple options that belong to a same group, except for the first group of questions that are used to assess the background experience of the surveyed participants. The answers are then computed to find the average score of each option per group, which allows for an understanding of the opinion tendencies of the participants. To analyse and compare the survey OAHP results, it is required for the data to be in the same format as the OAHP assessment discussed in Section 3, which consists of the comparison matrices with final attributed weights and CR. Generating these comparison matrices artificially was necessary, otherwise the survey would have been extremely long and most likely non of the surveyed participants would participate. Adopting this method of artificially generation allows for the 13 groups of questions to be extremely simplified, reducing the overall required inputs from 406 to 98, which means that it reduces the length of the survey in approximately 4,1 times. To produce these comparison matrices, a python algorithm was developed that uses the average scores of each option to artificially generate the relative comparison scores between each option of the same group, populating the matrices.

5.2. Python Algorithm Description

The pseudocode of the python algorithm used to generate the comparison matrices is shown bellow:

Algorithm 1 Generate OAHP Comparison Matrices

```
get data from survey excel tables
store data in two identical declared lists: $r_i$ and $c_j$
for all elements in $r_i$ and $c_j$ do
    if element is empty then delete element
    else if element not integer then round element
    end if
end for
declare square matrix of size equal to lists size
fill matrix with zeros
for all index i within $r_i$ do
    for all index j within $c_j$ do
        if $r_i > c_j$ then $M_{i,j} = r_i - c_j + 1$
        else if $r_i < c_j$ then $M_{i,j} = \frac{1}{(c_j - r_i)+1}$
        else$M_{i,j} = 1$
        end if
    end for
end for
display $M_{i,j}$
```

5.3. Transportation Systems Comparative Analysis

Throughout the comparative analysis between both OAHP results, the weights outputted from the comparison matrices will be presented in bar graphs for a better visualisation of the results. In the produced graphs, each assessed option will have two bars. The bottom bar in blue is the reference to the survey OAHP results and the top bar in orange is the reference to the OAHP results obtained in Section 3 based on the values defined by the author of this document.

The survey results were compared with all the comparison matrices produced up until this point, including TS comparison matrices, Evaluation Criteria comparison matrices and Feature Analysis comparison matrices. To better understand the results produced in the survey section, an example shall be given bellow.

The replacement ability survey OAHP results seen in Figure 7 show that the participants attributed more weight to the technology maturity, which refers to how much a technology has proven itself in an industry by performing real operations. The results also show that less importance was attributed to the sustainability criterion, which addresses the estimated longevity of a technology (eg. for how long a technology will maintain its relevance in the market and thus be supported by its manufacturer). On the other hand, the OAHP results show that the equipment complexity and the replacement difficulty are the most important criteria, this is justified by the reliability of the technologies, which ensures that they are easy to replace by not having hard to acquire technologies and by receiving constant support from their manufacturer. Analysing the standard deviation of the answers to each option, they fluctuate between 0.94 and 1.93, averaging 1.43. These values show that there is a considerable level of agreement between the participants opinions.

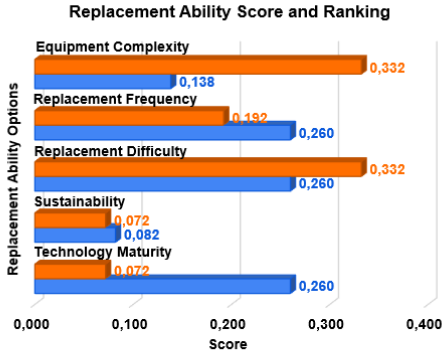


Figure 7: Replacement Ability scoring results

6. Hybrid Selection Method

Performing the selection of new technologies and TS using the OAHP method is an extensive procedure that requires many comparative evaluations, $N_{comparisons} = \sum_{n=1}^{c} k_n \frac{(k_n-1)}{2}$, where c is the number of matrices/criteria used to perform the evaluations and k is the number of assessed options in each matrix/criterion. For eg. in the case of Section's 3 OAHP, eighteen matrices are produced, each one with multiple options that result in 785 total comparisons made ($N_{comparisons} = 785$). In addition, the OAHP method is not easy to expand assessed options, since it requires performing a comparative analysis between all the previous options and the new ones, and to recalculate every option's weight per criterion. Also, the OAHP is a method that does not benefit from being automated.

On the other hand, the sifting method for selection is a method that is less time consuming, expands well and allows for a certain degree of automation. This method requires as input the features of the options and an optimal model or set of optimal features for comparison, that approximates to the desired solution. The main disadvantage of the sifting method is the necessity of an initial concept of what the best possible solution should look like.

Using the results obtained from the OAHP, it is possible to come up with an optimized model of the TS that can be used as a baseline to feed the sifting method, which would use this model to perform a sifting through various input options. The evaluation would be performed in terms of similarities between the options and the optimal TS model.

This means that such process relies in three main phases:

1. The understanding of the individual features performance for a case scenario, through OAHP evaluation.
2. The interpretation of OAHP results to design an optimized TS model for such case scenario with clearly identified features.
3. The use of the extracted model to build a final evaluation method through the use of sifting, where the sifting method takes all options and sifts them trough various levels until the best option/options is/are left.

As a follow-up from the OAHP and survey OAHP analysis, two optimal models are built. One is based on the OAHP results explained in Section 3 and the other is based on the results from the survey OAHP, explained in Section 5.

The first step is to analyse the criteria relevance that is evaluated through the OAHP and set a hierarchy between them. This process is repeated for both OAHPs and some relevant differences are expected. The second step is to assess the results from the features OAHP and to determine the best evaluated feature that addresses each criteria. Once again, this process is repeated for both OAHPs and some relevant differences are expected. Finally, these steps produce two optimal models and an idea of all the sifting levels that are performed during the evaluation. The order of the sifting levels will differ between the hybrid selection method (HSM) applied to the OAHP and applied to the surveyed OAHP.

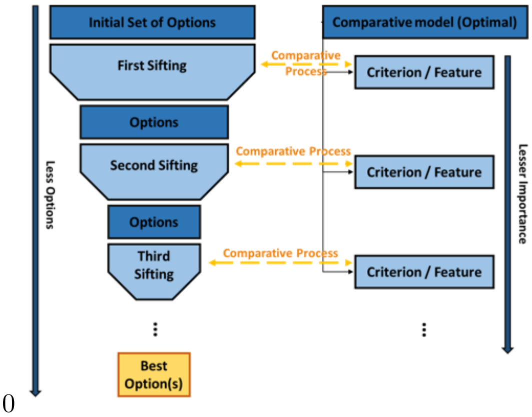
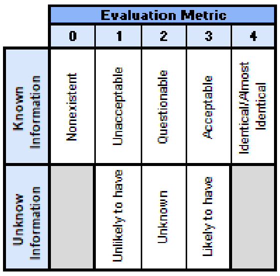


Figure 8: Sifting Method

To perform this evaluation, a comparison metric needs to be established. Inspired on the qualitative assessment of the OAHP metrics (seen in Figure 2), the HSM uses a similar metric, depicted in Figure 9, that evaluates the level of similarity between the option's feature and the optimal model's feature.



	Evaluation Metric				
	0	1	2	3	4
Known Information	Nonexistent	Unacceptable	Questionable	Acceptable	Identical/Almost Identical
Unknow Information		Unlikely to have	Unknown	Likely to have	

Figure 9: Metric code for qualitative comparison

6.1. Results Analysis

For the results of the first HSM, that concerns the author's OAHP, only 4 out of the 13 TS made it through the sifting process, the KOMAGV, the CTC, the MWOMP, and the SMF. It is worth mentioning that except for the CTC, all the other options ranked in the top 3 according to the OAHP results, which already shows congruence with the expected results. As for the results of the second

HSM, that concerns the surveyed OAHP, 4 out of the 13 TS also made it through the sifting process, the PT, the KOMAGV, the MWOMP, and the SMF. The results are as expected where the PT was the preferred solution and the other three options all ranked equally in second place.

To further analyse the results obtained from both HSMs, several radar graphs were used to plot the final selected options and their performance, where the area of each option in the graph is calculated and used as a final score to rank only the selected options. To exemplify the use of the radar graphs, Figure 10 is used to show the results for the 4 best ranked options of the HSM based on the survey's OAHP.

The graphs from Figure 10 correspond to the results of the HSM with use of the author's OAHP to design the optimal model. According to the calculations of the areas, the options ranked as follows: The MWOMP with a score of 40.02 out of 50 (score of the optimal model), the SMF with a score of 38.78, the KOMAGV with a score of 38.63 and the CTC with a score of 29.36. The first three ranked options clearly have a closer score when compared with the fourth ranked option, this is something that is also observed when analysing the OAHP results.

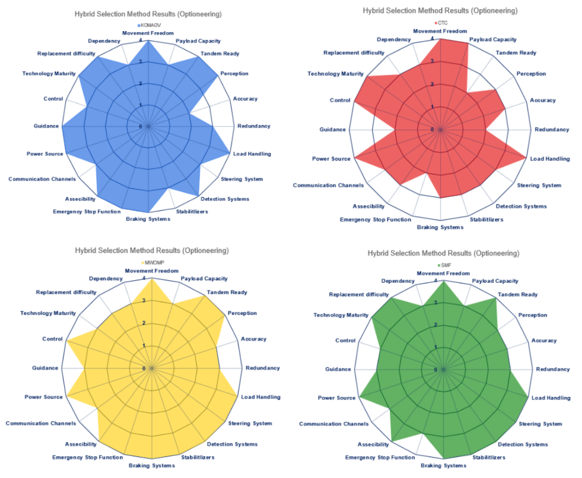


Figure 10: Hybrid Selection Method with author's Optioneering: KOMAGV(blue), CTC(red), MWOMP(yellow), SMF(green)

The HSM proved itself simple to utilize and less time-consuming than regular OAHP since comparisons are only done between each option and the optimal model and in terms of similarity, which reduces the required number of comparisons. In addition, the HSM is simple to expand, if a new option is added to the selection process, it is as simple as adding a new column to the table and performing a comparative analysis between the option's features and the optimal model's features following the proposed metrics.

7. Conclusions

According to the author of this document's OAHP, produced in Section 3, the TS with the highest score is the KOMAGV and the TS with the worst score is the PT. The author of this document also mentions the MWOMP and the SMF as two extremely relevant options due to their pallet transportation design, high capability for tandem operations, adequate payload capacity (> 100 tons alone or in tandem), and omnidirectional locomotion.

As previously explained, the OAHP results depend on the quality of the data used. Data refers to the content of the comparison matrices that represent the qualitative comparison between options, and the quality of the data refers to the consistency of the values and how accurately those values represent reality. The need to assess the quality of the data used in Section 3 led to the development of the survey discussed in Section 5. The survey was developed to collect the participants' opinions, who have experience with remote handling, to produce a similar OAHP to the one in Section 3. Having two OAHPs, one from the author of this document and the other produced from the participants' inputs to the survey, allowed for the comparison between both OAHPs' results.

In Section 6, two HSMs are developed using two different optimal models, one derived from the author's OAHP and the other from the survey OAHP. After performing the selection process with both HSMs, the obtained results were compared with both OAHPs (author's OAHP and survey OAHP). The results of the author's HSM and OAHP were very similar, as well as the results of the survey HSM and OAHP. Taking into consideration that the results were similar and that the HSM has advantages of both the Sifting and the OAHP without having the major disadvantages of the OAHP, the HSM proves that it can be an improvement as a selection method.

8. References

[1] *The demonstration power plant: DEMO.* EUROfusion. Accessible at: `https://www.euro-fusion.org/programme/demo/`, (last accessed on 27/09/2022).

[2] Alberto Vale. FFMECA and recovery strategies for ex-vessel remote maintenance systems in DEMO. *Fusion Engineering and Design*, 124:619–622, 2017. Proceedings of the 29th Symposium on Fusion Technology (SOFT-29) Prague, Czech Republic, September 5-9, 2016.

[3] *Robotic systems for safe nuclear decommissioning.* KUKA Systems. Accessible at: `https://www.kuka.com/en-de/industries/other-industries/nuclear-decomissioning`, (last accessed on 27/09/2022).

[4] *Automated guided vehicle systems.* KUKA Systems. Accessible at: `https://www.kuka.com/en-de/products/`

mobility/automated-guided-vehicle-systems, (last accessed on 27/09/2022).

[5] Taylor More. *Robots for nuclear power plants.* IAEA Bulletin, 1985.

[6] Richard Smith, Elisa Cucco, and Colin Fairbairn. *Robotic Development for the Nuclear Environment: Challenges and Strategy.* 2020.

[7] K. Priyanka and G. V. Barani Krishnan. *Robotics for Nuclear Power Plants.* International Journal of Engineering Research Technology (IJERT), 2018. Volume 6, Issue 14.

[8] James P. Trevelyan, Sung-Chul Kang, and William R. Hamel. *Robotics in Hazardous Applications.* Springer, 2008.

[9] T. Abrahamsen and E. Aven. On the use of cost-benefit analysis in ALARP processes. *International Journal of Performability Engineering*, 3(3):345, 2007.

[10] *Technology Readiness Level: Como Funciona o método TRL.* Biotech Town, 2021. Accessible at: https://biotechtown.com/blog/trl/, (last accessed on 27/09/2022).

[11] Gil, Luís, Andrade, Maria Hermínia, Costa, and Maria do Céu. Os TRL (technology readiness levels) como ferramenta na avaliação tecnológica. *Revista Ingenium*, pages 94–96, 2014.

[12] K. Priyanka and G. V. B. Krishnan. Robotics for nuclear power plants. *International Journal of Engineering Research Technology (IJERT)*, pages Volume 6, Issue 14, 2018.

[13] W.R.H.James, P. Trevelyan, and Sung-Chul Kang. Robotics in hazardous applications. *Springer*, 2008.

[14] *Pallet Transporters.* Fetch Robotics. Accessible at: https://fetchrobotics.com/pallettransport1500/, (last accessed on 27/09/2022).

[15] Seaqx. *Mobile Gantry Cranes.* Accessible at: http://www.seaqx.com/content/products.php?page=gantry, (last accessed on 27/09/2022).

[16] *Re-sizable multipurpose vehicles.* Seaqx. Accessible at: http://www.seaqx.com/content/products.php?page=adaptable, (last accessed on 27/09/2022).

[17] *Self Propelled Modular Transporters.* Seaqx. Accessible at: http://www.seaqx.com/content/products.php?page=spmt, (last accessed on 27/09/2022).

[18] *Tooling Production Platform.* Seaqx. Accessible at: http://www.seaqx.com/content/products.php?page=prodplatforms, (last accessed on 27/09/2022).

[19] *Extra low production line platforms.* Seaqx. Accessible at: http://www.seaqx.com/content/products.php?page=assyplatforms, (last accessed on 27/09/2022).

[20] *KUKA omniMove (AGVs).* KUKA. Accessible at: https://www.kuka.com/en-de/products/mobility/mobile-platforms/kuka-omnimove, (last accessed on 27/09/2022).

[21] *KUKA Mobile Platform 1500.* KUKA. Accessible at: https://www.kuka.com/en-de/products/mobility/mobile-platforms/kmp-1500, (last accessed on 27/09/2022).

[22] *50 Tons Coil Transfer Carts.* New World Trasnfer Car. Accessible at: https://www.newld-transfercar.com/coil-transfer-vehicle/coil-transfer-car/50-tons-coil-transfer-carts.html, (last accessed on 27/09/2022).

[23] *Mecanum Wheel Omnidirectional Mobile Platform.* Heavy Duty AGV. Accessible at: https://heavydutyagv.com/index.php/products/mecanum-wheel-mobile-platform, (last accessed on 27/09/2022).

[24] *Shifter Trailer.* AVT/Shifter. Accessible at: https://www.shifter-avt.com/products/shifter-trailer, (last accessed on 27/09/2022).

[25] *Shifter Mono.* AVT/Shifter. Accessible at: https://www.shifter-avt.com/products/shifter-mono, (last accessed on 27/09/2022).

[26] *Shifter Flex.* AVT/Shifter. Accessible at: https://www.shifter-avt.com/products/shifter-flex, (last accessed on 27/09/2022).

[27] *Shifter Multi Flex.* AVT/Shifter. Accessible at: https://www.shifter-avt.com/products/shifter-multiflex, (last accessed on 27/09/2022).

[28] Oliver Crofts, Antony Loving, Marc Torrance, Stuart Budden, Ben Drumm, Tristan Tremethick, Didier Chauvin, Mikko Siuko, William Brace, Viktor Milushev, Martin Mittwollen, Timo Lehmann, Felix Rauscher, Georg Fischer, Paolo Pagani, Yan Wang, Carsten Baars, and Alberto Vale. EU DEMO remote maintenance system development during the pre-concept design phase. *Fusion Engineering and Design*, 179:113121, 2022.

[29] Alberto Vale and José Dias. Path planning and space occupation for remote maintenance operations of transportation in DEMO. Fusion Engineering and Design Vol. 146, Part A, (2019) 325-328. DOI: 10.1016/j.fusengdes.2018.12.057.

[30] Alberto Vale, Rodrigo Ventura, Pedro Lopes, and Isabel Ribeiro. Assessment of navigation technologies for automated guided vehicle in nuclear fusion facilities. Robotics and Autonomous Syste ms Vol. 97 (2017) 153-170. DOI: 10.1016/j.robot.2017.08.006.

[31] *What is MCDM/MCDA?* A Thousand Minds. Accessible at: https://www.1000minds.com/decision-making/what-is-mcdm-mcda, (last accessed on 27/09/2022).

[32] S. Deo, D. Gilmore, M. Thof, and J. Enriquez. Infrastructure optioneering: An analytical hierarchy process approach. pages 957–969, 06 2016.

[33] R. Archer, S. Paisley, M. Essat, L. Preston, and M. Thornhill. Iterative sifting in the selection of research evidence: Implications for reviews and other decision problems. *International Journal of Technology Assessment in Health Care*, pages 31:1/2, pp. 54–58, 2015.

[34] T. L. Saaty. *How to make a decision: The Analytic Hierarchy Process.* European Journal of Operational Research, 1990. vol. 48, no. 1, pp. 9-26.

[35] J.A. Alonso and M. Lamata. *Consistency in the Analytic Hierarchy Process: a New Approach.* International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, 2006. vol. 14, pp. 445-459.