UKAEA-RACE-PR(19)01

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This is a preprint of a paper submitted for publication in
Fusion Engineering and Design

Concept selection of the Automated Inspection and Maintenance Test Unit for the EU DEMO using a novel fuzzy-based decision support tool

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Systems Engineering (SE) allows addressing the design of complex systems from a holistic standpoint, starting from the early stage of development until the end of its lifetime. Using a SE approach, all the stakeholders' needs can be considered, and different design alternatives can be proposed, taking into account requirements coming from all the different fields connected to component design. Adopting this approach, the ranking of the proposed design alternatives can be carried out using Multi-Criteria Decision Making (MCDM) methods, which foresee the involvement in the decision-making process of a team of experts operating in a participative way. Among MCDM methods, those based on fuzzy logics allow taking into consideration the different shades typical of the experts' judgement, as the same evaluation might produce different meanings for different people. Fuzzy-based MCDM methods could be advantageous whenever the decision-making process is mainly based on experts' experience and sensibility, because quantitative data are missing and/or the project is in the very early stage where there is a lack of reliable quantitative information. This is the typical case of R&D activities on nuclear fusion, where big projects (ITER, DEMO) must contend with significant uncertainties. Therefore, a SE approach involving the application of MCDM methods could help to improve the progress of these projects reducing the margins of uncertainty. Several applications are recalled in this paper and a further case study, regarding the Automated Inspection and Maintenance Test Unit (AIM-TU) concept design, is presented. In the framework of EU DEMO project, the AIM-TU has been proposed to provide to the international community a facility able to perform, with high reliability, robotic maintenance and inspection procedures in DEMO-oriented environments. In this paper the SE approach has been applied to the AIM-TU concept selection, adopting the fuzzy Analytic Hierarchy Process (FAHP) MCDM method for the best option selection. To this purpose, a novel fuzzy-based decision support tool named ELIGERE has been used. It enables a practical implementation of the FAHP method, speeding up the decision-making process and improving its quality by ensuring the independence of each expert evaluation from the opinion of the other team members.

Keywords: AIM-TU, Systems Engineering, MCDM, FAHP, DEMO, ELIGERE.

1. Introduction

The design of a nuclear fusion system is an inherently multidisciplinary problem, involving multiple aspects coming from different fields. Further, its complexity typically involves a high number of sub-systems, interfaces and consequent even novel requirements that must be considered. Thus, addressing the design of the most challenging nuclear fusion systems [1][2][3][4][5][6] requires a holistic approach from the earliest design stage, so that all the stakeholders' views can be considered through the complete process lifecycle. This allows multidisciplinary teams to contribute to the design process together in a systematic way.

To comply with this view, the Systems Engineering (SE) methodology has been increasingly adopted in the nuclear fusion international community in the last decade. Its implementation from the early stage of R&D activities is nowadays a *must* in the most important international fusion technology projects, such as the ITER and EU DEMO reactor designs [7][8][9].

Adopting the SE approach in the early concept design phase, all possible design configurations could be taken into account. The different alternatives which are developed at this stage are then compared to choose a best candidate, on the basis of selection criteria which consider all the fields involved in the design activities. To this end, Multi-Criteria Decision Making (MCDM) methods can be used. These methods allow identifying the factors which are important in making a decision, and then ranking them in a hierarchical structure so that a panel of experts can perform a systematic, pairwise comparison of the potential design alternatives [10].

A broad application of SE principles integrated with MCDM methods could have a great impact in supporting R&D teams working in complex scenarios such as nuclear fusion technology. For example, these methods could efficiently be used to select the design concepts of key systems in fusion research, such as the breeding blanket [11][12][13][14]. However, implementing decision making sessions can be time-consuming, especially when a large number of alternatives and criteria are under consideration, or when information is scarce, and the range of uncertainty is wide at such early design stage.

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Further, complex multidisciplinary problems may require many different experts, but usually, the higher the number of people involved in the discussion is, the slower the decision-making becomes. Therefore, taking advantage of MCDM approaches requires practical implementation methods which can help in speeding up the decision-making sessions and allow the participation of multiple experts without their mutual influencing affecting the quality of the process. To this end, the use of ELIGERE web platform [15][16] provides a simple, easily accessible and consistent interface that enables collecting and post-processing of experts' input into a MCDM process through an online questionnaire format. Its flexibility and ease of use speed up the selection procedure, especially when compared to traditional spreadsheet-based implementations, where panel members fill in a custom data sheet and then a survey administrator must integrate the individual results and generate the best solution. Moreover, since experts are often busy people, simpler processes with less cognitive loading on them are usually preferred [10]. In this regard, the flexibility of being able to access the web platform at a time convenient for the expert also reduces difficulties in scheduling joint decision-making sessions, which are a source of very significant time delays to the process. Further, ELIGERE can take any number of expert inputs, meaning that it removes the practical limitations in the number of experts that compose the panel. This is of particular importance to large, complex design exercises such as those common to nuclear fusion. Thus, an automatic software framework for concept selection shows clear practical advantages over traditional methods.

In this paper, an overview on the main application of MCDM methods in nuclear fusion technology is given in section 2, together with a brief explanation of the main rationale and features of the ELIGERE platform. Moreover, the case study of the Automated Inspection and Maintenance Test Unit (AIM-TU) is presented in section 3, in order to show a typical situation where the SE approach endowed with MCDM methods leads to a rationalised selection of a design option for a nuclear fusion-oriented facility. The SE activities aimed at the AIM-TU concepts generation are detailed in section 3 as well. Section 4 describes the implementation of a MCDM method to reach a final concept selection for AIM-TU, using the ELIGERE web platform. Finally, conclusions are discussed in section 5.

2. State of the art

In this section we present a brief overview of the most adopted MCDM methods and how these methods have been applied so far in the nuclear fusion context.

2.1 Overview of MCDM methods

MCDM methods aim at supporting decision makers in the subjective evaluation of criteria and alternatives in many fields of applications: management, business, finance, healthcare, technology, engineering, etc. A huge amount of methods has been developed over the years [17]. Among them, according to a recent review article [18], the most diffused approaches are the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

AHP is a theory of measurement through pairwise comparisons and relies on the judgments of experts to derive priority scales [19]. It decomposes a complex problem into a hierarchical structure of objectives, criteria, sub-criteria and alternatives. A scale of relative importance allows representing, in the form of a pairwise comparison, the expert verbal judgments, which are quantified using crisp numbers.

TOPSIS is an approach to identify an alternative which is closest to the ideal solution and farthest to the negative ideal solution in a multi-dimensional computing space [20]. The main idea of TOPSIS is that the optimal alternative should not only have the shortest distance from the positive ideal solution, but also have the longest distance from the negative ideal solution.

In real world problems, natural language is often employed for judgment. However, MCDM algorithms must rely on numbers. The main issue is that associating linguistic variables with crisp numbers might be inappropriate, since the same words might have a different meaning for different people. To overcome this problem, fuzzy numbers are introduced to help linguistic variables to be expressed appropriately. When fuzzy set theory [21] is used to enhance MCDM problems, we refer to fuzzy multi-criteria decision-making (FMCDM) methods. Accordingly, fuzzy AHP (FAHP) and fuzzy TOPSIS have been introduced respectively in [22] and [23]. To date, they rank as the two most used FMCDM approaches [18].

2.2 MCDM methods in nuclear fusion technology

Within the framework of R&D activities promoted and supported by the EUROfusion consortium [24], MCDM methods and techniques have been adopted in the early stage of the design of some critical components of the EU DEMO nuclear fusion reactor. To date, the most used approaches for fusion engineering applications have been the AHP and FAHP methods.

In particular, the EU DEMO Divertor, Breeding Blanket and Remote Maintenance project teams have used the AHP and FAHP methods to carry out the conceptual design of: Divertor-to-Vacuum Vessel locking system [25][26], the Divertor Cassette [27], the Divertor Remote Maintenance Port [28] and the Breeding Blanket Transporter [29].

In all these studies, teams of experts have been involved in brainstorming sessions in order to select the best concept from all the possible design options in a participative way. Since the EU DEMO reactor is still in its pre-conceptual phase and it sees several parties involved for the design of a single component, this approach is valuable as it allows the management of such a complex design. In this way, all the stakeholders' needs are taken into account from the early stage of the component design. Moreover, the brainstorming sessions have allowed establishing the evaluation criteria to be used in the best option selection. Due to their origin, criteria defined in this way are sufficiently representative of all the stakeholders' standpoints.

Once the possible design solutions and the selection criteria have been identified, their comparison, evaluation and the selection of the best solution have been performed using AHP or FAHP techniques. Previous works have used two different panels of experts for the evaluation of criteria (first phase of the method) and the evaluation of the alternatives (second phase of the method) respectively, in order to ensure the independence of the best option selection.

The results of the above-mentioned studies show how the application of the MCDM methods is considered necessary for many fusion-related designs. The rationalised approach leads to more a collaborative and transparent selection of component concepts, ensuring that the chosen designs consider all relevant technical requirements, even if these stem from a wide range of stakeholders with varied areas of expertise. However, as the complexity of designs grows, the use of MCDM methods can become cumbersome if appropriate tools are not used. None of the previous works on nuclear fusion research have used a systematic decision support software tool to carry out the concept selection, so the processes can be time-consuming and inflexible. Thus, we show how a novel system can improve the implementation of decision-making sessions when a high number of criteria, alternatives and experts are foreseen.

2.3. The ELIGERE web platform

ELIGERE is a decision support framework for ranking multiple design alternatives according to different evaluation criteria. The framework is based on the assessment of questionnaires submitted via a web interface to a panel of experts, which are asked to compare, in a pairwise manner, first the criteria and then the alternatives involved in the study. Its computational engine is based on FAHP [30]. The method foresees the following steps: (1) translation of the judgments of the experts in fuzzy numbers; (2) computation of the fuzzy comparison matrix, which summarizes the judgments of the experts; (3) defuzzification process through the extent analysis [31] to rank criteria and alternatives.

ELIGERE framework provides several features of interest for concept selection: (i) setup of the decision session and of FAHP questionnaire using a pre-defined web format; (ii) filling of the questionnaires via a web interface, such that the experts can participate in the decision session remotely; (iii) automatic computation of the optimal concept solution once the answers from experts are available on a database; (iv) data collection of results in a permanent database. The framework has been released under GNU general purpose license [32]. For a deeper understanding of the ELIGERE platform, the readers can refer to [33]. A video on the use of ELIGERE platform can be found in [34].

To date, this decision support tool has been successfully used for concept selection in different scenarios: layout of a robotic cell [35], design of a 5-DoF robotic manipulator [36], design of a 3D body scanner [37] and design of sport equipment [38].

In this work ELIGERE is used for the concept selection of the AIM-TU facility, showing the advantages in adopting this kind of tool for a nuclear fusion-oriented test facility. Its flexibility allows experts to easily evaluate concepts in a qualitatively way. Moreover, its web-based form allows the experts to perform the evaluation individually, avoiding their mutual influence during long and animated brainstorming sessions. These characteristics are very important in fusion technology, where the complexity and current design uncertainty means the sensibility of the experts often plays a pivotal role.

3. AIM-TU concept generation

The combined application of a SE approach and MCDM techniques to fusion technology is valuable, because R&D is typically carried out with relatively uncertain requirements. In this context, the conceptual design of the AIM-TU facility represents a relevant case study because of its indefinite project boundaries and its relevance to the EU DEMO robotic maintenance development. The complete SE procedure followed to select a concept for the AIM-TU facility is summarized in Figure 1. The steps represented by pale blue boxes have been addressed only by the AIM-TU design team, whereas the last step (represented by a pale green box) has involved a larger panel of experts for the MCDM aimed at the concept selection.

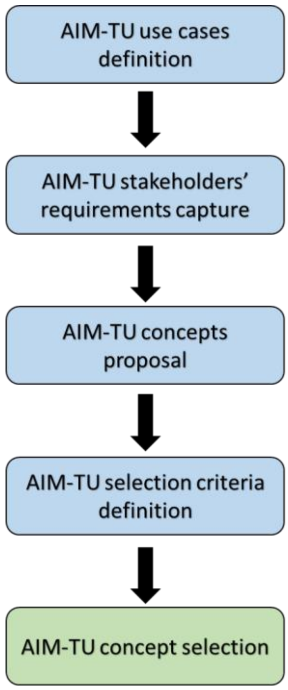

Figure 1. The complete SE procedure followed to select a concept for the AIM-TU facility.

3.1. The AIM-TU case study

The rationale behind the AIM-TU project is to realize a facility that enables testing and validation of automated robotic maintenance, in environments representative of the EU DEMO fusion reactor. Therefore, the AIM-TU design must consider how best to provide a versatile test platform in which robotic systems perform a wide range of maintenance operations. However, given that the EU DEMO design is still in a pre-conceptual phase, very few details are fixed regarding the maintenance systems and the operations they will be conducting. This represents an ideal case study to demonstrate the strength of the SE approach combined with MCDM methods for tackling abstract, multidisciplinary projects with high uncertainty.

In particular, this approach allows selecting a concept for the AIM-TU design which represents the best trade-off solution among several constraints. The main considerations to balance are: the impact on other tools and facilities already operating on the construction site, the quality of the tests, their environmental independence, how well they represent DEMO maintenance operations; the safety of the test execution, cost, the ease of use and reconfiguration and, lastly, versatility.

3.2. The AIM-TU facility

The AIM-TU project is part of the studies linked to the EU DEMO, being framed within the remote maintenance R&D activities. Automation is seen as a key technology for reactor maintenance, necessary to reduce shutdown durations and achieve commercially-relevant plant availability. To this end, it is necessary to design, procure and build a test unit where researchers could conduct tests specifically focused on investigating, and demonstrating, how typical remote maintenance tasks can be automated.

The test unit will allow simulated reactor environments to be set up to focus on automation research which is directly relevant to the EU DEMO machine. The objective is to design a test unit which is versatile enough to continue to expand and adapt to future research needs, generating expertise across EUROfusion partners.

The AIM-TU team have so far selected three general themes (Use Cases) of the tests that would be conducted. They are:

- delivery and exchange of consumables (Use Case 1);
- replacing hardware (Use Case 2);
- periodic inspection of hardware (Use Case 3).

The three Use Cases are based around demonstrating inspection tasks (where the remote maintenance system can sense, but not change, the reactor environment) and maintenance tasks (where some modification to the reactor environment is undertaken, such as replacing a damaged item). A wide range of tests should be possible.

Experiments are envisioned to involve a test environment simulating a DEMO internal location (for example, a narrow port inside the vessel, a nest of pipes in the ex-vessel area, etc.), into which a robotic agent would be deployed in order to perform the tasks. Although the project scope excludes tests with active radiation sources due to the additional logistical and safety challenges associated, the consequences of such harsh conditions will be simulated where it is relevant. For instance, AIM-TU may avoid using sensors which would not survive the radiation levels in an in-vessel scenario, or artificially modify their output to replicate accelerated degradation.

As a versatile platform, AIM-TU must allow a wide range of different tests to be performed, and to adapt the testing schedule to the various findings of the performed research. One desired feature of AIM-TU is that it can be expanded beyond this first set of Use Cases, to include other potential tests in future (for example, demonstrate it can autonomously decontaminate equipment, clean up a fluid leak, or commission reactor diagnostics).

The project assumes AIM-TU would be built at the United Kingdom Atomic Energy Authority site in Culham (UK), under supervision of the Remote Applications in Challenging Environments (RACE) department. The facility would be sited either in RACE's workhall or in a dedicated building.

The AIM-TU will be endowed with a set of "robotic agents", namely the automatic tools capable of performing operations acting on the "simulated hardware", the components representing DEMO reactor hardware. Moreover, other "test hardware" will be required, namely equipment to facilitate the tests such as sensor supports, cabling infrastructure, safety equipment, etc.

3.3. Stakeholder requirements capture

For the considered three Use Cases, which cover a wide range of possible tests, stakeholder requirements were captured according to the SE approach. The rationale behind the stakeholder requirements capture was to make AIM-TU operations as close as possible to the DEMO robotic maintenance scenarios, recognizing the considerable associated uncertainty. Therefore, the AIM-TU team arranged brainstorming sessions with stakeholders to capture their requirements concerning the selected use cases.

This participative procedure allowed selecting a list of 57 stakeholder requirements, extracted from a longer list through an iterative process of requirement refinement. Moreover, six requirements categories were selected [39] and the requirements grouped accordingly. The considered categories are:

- Performance (32 requirements);
- Safety & Environmental (13 requirements);
- Project (4 requirements);
- Maintenance (4 requirements);
- Quality/Reliability (2 requirements);
- Installation (2 requirements).

At the end of this phase, a preliminary Stakeholder Requirements Document was released.

As to the performance requirements, the main rationale is to consider the mission of the selected Use Cases related to maintenance and inspection. To this end, it has been considered that different tests should be possible, previously arranged by human facility operators.

Moreover, several types of hardware will be replaced in DEMO, so the automated maintenance system must be capable of recognizing them in order to perform the pertinent procedure. Simulating significant failure scenarios is beyond the scope of the AIM-TU at this stage, so the condition of the simulated hardware must be such that replacement is possible.

Regarding the Safety & Environmental requirements, the main rationale is that the performed operations do not jeopardise the human operators or AIM-TU systems.

Project requirements mainly concern the schedule and documentation of AIM-TU test campaigns.

Lastly, Maintenance, Quality/Reliability and Installation requirements are independent from the considered Use Cases, and reflect the general considerations necessary for the correct operation of AIM-TU.

3.4. AIM-TU concept generation

The AIM-TU team produced three concepts, down selected from a variety of concepts generated in a brainstorming session. The concepts to be taken forward in the selection process all met the stakeholder requirements and were sufficiently different to allow a clear comparison between them from various standpoints.

The first proposed concept was the *Toy Box* (Figure 2). Here, AIM-TU would consist of a collection of testing equipment, deployed in the RACE workhall to perform specific tests and then dismantled. When not in use, the equipment would be efficiently stored in a convenient location out of the way of other activities. This would provide maximum test versatility and allow AIM-TU to easily adapt to the schedule of the testing space (e.g. RACE workhall). The concept would allow multiple tests with different requirements to be carried out in parallel, in different locations, and even complement other RACE test programmes.

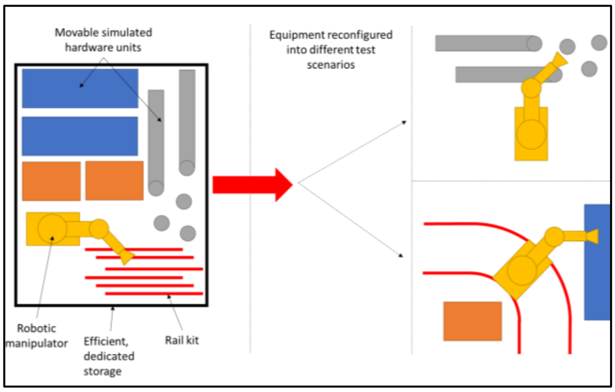

Figure 2. The *Toy Box* concept.

The second concept was the *Containerised Units* (Figure 3). It proposed housing AIM-TU tests within ISO containers. This would give a series of discrete, standardised test spaces, which could be stacked and linked to progressively increase the capability of AIM-TU. The containers are mobile and they provide versatile installation and storage options. For instance, they could be housed on the UKAEA site and brought in to the RACE workhall to conduct tests which require other RACE existing infrastructure and hardware. The containers would also provide good testing infrastructure, with 6 face attachment, and their standardised properties (size, mass, strength, materials, etc.) would simplify design.

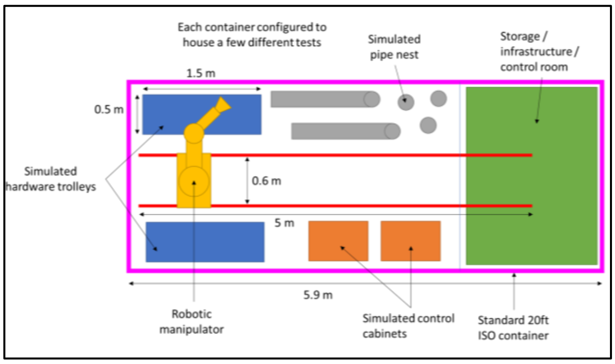

Figure 3. The *Containerised Units* concept.

The third concept is the *Dedicated Structure* (Figure 4). It proposed building a dedicated space to house AIM-TU. This would provide a more permanent facility with standard building infrastructures. A large space could be specified to house both testing and storage. The permanent infrastructure would minimise setup time and costs,and also reduce the need for recalibration of testing equipment after each reconfiguration. Environmental control to ensure test quality would be easy to achieve. As a more standard approach, expertise would be more readily available to assist with design, construction, planning permissions, etc.

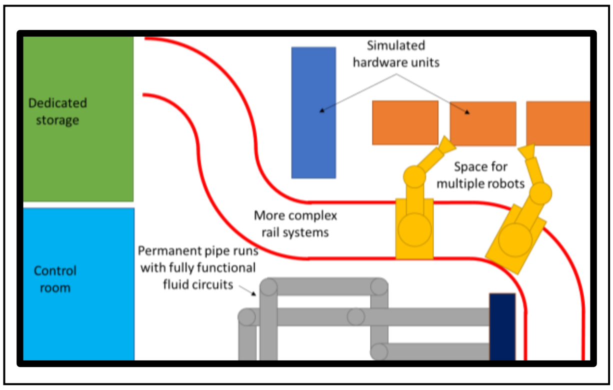

Figure 4. The *Dedicated Structure* concept.

4. AIM-TU concept selection

After the requirements capture and the proposal of the three design concepts, the optioneering phase was launched in order to select the best option for the AIM-TU design.

4.1 Definition of the selection criteria

Starting from the stakeholder requirements, the AIM-TU team defined ten selection criteria by means of further brainstorming sessions supported by a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis of the three proposed concepts. The application of the SWOT analysis is a well-known and well-diffused approach to pinpoint evaluation factors, such as evaluation criteria [40][41].

As an example, the SWOT analysis table relevant to the *Toy Box* concept is reported in Figure 5.

Strengths	Weaknesses
• Reduced upfront infrastructure costs • Temporary, so less impact on deployment area • No restrictions on space (apart from building it's set up in) • Lower weight • Not fixed to one design • Minimum storage space • Can easily deploy with TARM. • Different requirements for each test, so difficult requirements do not limit all tests	• Considerable set up costs • Requires some existing infrastructure (e.g. storage) • Less repeatable • Needs safety separately + safety case • Increased setup time and effort • Each test would require significant commissioning • Each test would require significant calibration
Opportunies	**Threats**
• Bigger robots • Easily sellable in bits • Growable • Can integrate with existing tests/facilities • Would easily integrate with RMTF	• Will be put away and forgotten • Temporary, limits test evolution • May need lots of external storage • Documentation will be difficult • Not easy to use & set up, especially for external parties

Figure 5. The SWOT analysis table for the *Toy Box* concept.

Following this approach, a long list of criteria was compiled, and, from this, an iterative participative procedure allowed reducing the criteria number to the final ten (Table 1). The number of compared concepts and criteria determines the number of survey questions that must be answered by the experts, so it is desirable to reduce their number as far as possible.

Table 1. Selection criteria.

ID	Label	Criterion
1	Functional Performance	To enable testing which addresses relevant maintenance automation challenges in fusion environments.
2	Safety	To need fewer resources to meet all safety requirements.
3	Environment Independence	To be less affected by external influences during the tests.
4	Test Quality	To ensure test repeatability, monitoring and results capture.
5	Ongoing Project Risk	To impose the lowest burden on RACE workhall, staff organization, and budget.
6	Lowest Initial Resources	To require the lowest initial design and building resources.
7	Space	To make best use of space for testing, storage and integration with other RACE activities.
8	Ease of Reconfiguration	To require fewer reconfiguration resources in between tests.
9	Versatility	To be versatile and expandable.
10	Ease of Use	To be user friendly during testing.

As to criterion 1, it allows comparing alternatives on their potential to facilitate the setup and execution of maintenance automation technology demonstrators which are relevant to a fusion environment. AIM-TU should provide solutions to meaningful, high priority technical challenges. The preferred alternative should permit test environments to be made as representative as possible of the conditions likely to be encountered by autonomous systems in fusion reactors. Replicating radiation, large electromagnetic fields and high temperatures falls beyond the scope of AIM-TU, but the preferred option should allow their effect on the units-under-test to be simulated as far as possible.

Regarding criterion 2, it allows comparing alternatives on the ease of ensuring the necessary safety standards are met. The preferred alternative should require the fewest number of special safety procedures. The safety of humans in the proximity of AIM-TU at any time must be considered.

Criterion number 3 is based on the necessity to compare alternatives on their aptitude to be less influenced by factors external to the test in question. The preferred alternative should ensure the least impact from environmental conditions and disturbances which may affect test measurements, such as ambient temperature or lighting conditions.

Criterion 4 allows comparing alternatives on their aptitude to enable repeatable tests with well monitored and captured measurements. Firstly, the preferred alternative should allow efficient documentation, to achieve high test repeatability and robustness. Secondly, it should provide flexibility in deploying monitoring and control systems to allow a diverse mix of high-quality test measurements to be taken. Finally, the preferred alternative should be capable of capturing test results with the highest confidence and fidelity.

As to criterion 5, it allows comparing alternatives on their aptitude to minimise their burden on RACE beyond the AIM-TU project in terms of influence on the operation of the other mock-ups, amount of required resources and running costs, in order to maximise the long-term value for money.

Similarly, criterion 6 allows comparing alternatives on their initial design and building resource needs. The preferred alternative should be the easiest to design and build, at lowest cost and with shortest construction time. This ensures that project resourcing levels remain viable.

As far as criterion 7 is concerned, it allows comparing alternatives on their aptitude to best exploit the available surface, allowing storage and re-use of the AIM-TU area. Firstly, the preferred alternative should ensure an efficient use of space, with a high ratio between the active test environment and total occupied surface. Secondly, the preferred alternative should allow the easiest storage of the robotic agents, test hardware and auxiliary equipment.

Concerning criterion 8, it allows comparing alternatives on the resources they require when reconfiguring the test environment to conduct a different test, regardless of existing RACE infrastructure. The preferred alternative should ensure the best compromise between ease, speed and cost of reconfiguration.

Criterion 9 compares alternatives on their aptitude to be versatile and expandable. The preferred alternative should be the most versatile, allowing different types of tests to be performed, possibly in parallel. It should also present a modular layout/behaviour, providing the possibility of progressively growing the facility and/or its capabilities over time.

Lastly, criterion 10 compares alternatives on the ease of conducting tests. The preferred alternative should allow flexible interaction with the test environment, and convenient access for human operators. Further, the preferred alternative should allow the units-under-test to be easily and safely deployed within the test environment.

4.2 The concept selection using ELIGERE

To perform the AIM-TU concept selection, a questionnaire was provided to a panel of 10 experts. The panel was composed of the AIM-TU project leader, four EUROfusion grantees involved in the project, two systems engineers from RACE's DEMO office, two RACE engineers with extensive expertise in Remote Maintenance and the EUROfusion Remote Maintenance project leader.

Since the project is in a very early stage and quantitative information to support the decision-making process was unavailable, the FAHP MCDM method was chosen to conduct the selection. In this way the experts were able to give an initial, qualitative evaluation of the criteria and concept alternatives, making pairwise comparisons informed by their experience and sensibility.

The ELIGERE platform was used with a seven-value fuzzy scale (absolutely less important, less important, weakly less important, equally important, weakly more important, more important, absolutely more important). Figure 6 and Figure 7 show views of the ELIGERE web questionnaire set-up for the AIM-TU optioneering.

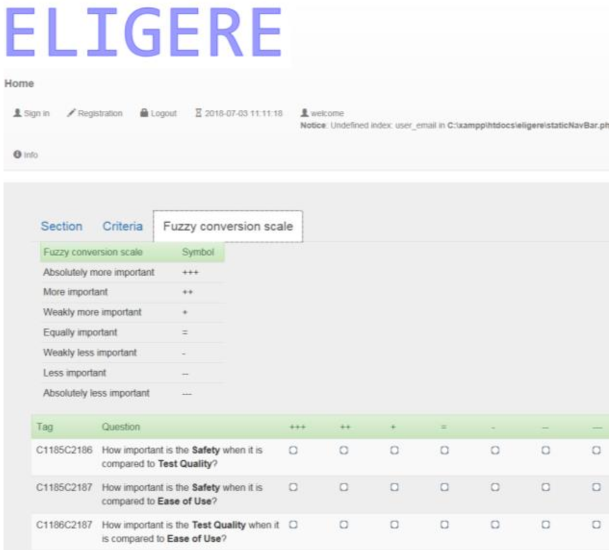

Figure 6. Eligere questionnaire: pairwise comparison of the criteria

Figure 7. Eligere questionnaire: the pairwise comparison of the alternatives. The pairwise comparison is made for each criterion separately.

The results of the pairwise comparison of the criteria are reported in Table 2. The Functional Performance, Environment Independence, Test Quality, Space, Ease of Reconfiguration and Ease of Use were judged as being marginally more important for the selection of the best option.

A standout observation is that all the considered criteria received overall similar weightings, indicating that the selected criteria are all relevant to the decision-making process. This is a further confirmation of the SE approach power, able to provide valuable criteria for the concept selection and to exclude, at the same time, non-significant aspects.

Table 2. Criteria weights.

ID	Criterion	Weight

1	Functional Performance	0.103
2	Safety	0.092
3	Environment Independence	0.103
4	Test Quality	0.103
5	Ongoing Project Risk	0.095
6	Lowest Initial Resources	0.099
7	Space	0.103
8	Ease of Reconfiguration	0.103
9	Versatility	0.095
10	Ease of Use	0.103

In Table 3 the ranking of the three proposed concepts versus the 10 criteria is reported.

Results show that the *Toy Box* concept is the best option on the basis of Ongoing Project Risk, Lowest Initial Resources, Ease of Reconfiguration, and Versatility criteria (criterion 5, 6, 8 and 9, with values in bold).

As to the *Containerised Units* concept, it is the preferred option from a Space perspective (criterion 7, value in bold), and it is a close second to the *Dedicated Structure* concept in the remaining criteria (Functional Performance, Safety, Environment Independence, Test Quality and Ease of Use).

Table 3. Concept scores against criteria.

Criterion ID	Criterion weight	Toy Box	Containerised Units	Dedicated Structure
1	0.103	0.285	0.326	**0.389**
2	0.092	0.155	0.412	**0.433**
3	0.103	0.191	0.361	**0.448**
4	0.103	0.259	0.333	**0.409**
5	0.095	**0.403**	0.347	0.250
6	0.099	**0.722**	0.463	-0.185
7	0.103	0.430	**0.493**	0.077
8	0.103	**0.414**	0.251	0.336
9	0.095	**0.506**	0.308	0.186
10	0.103	0.187	0.362	**0.450**

Lastly, applying the weights of Table 2 to the results reported in Table 3, the final ranking of the alternatives has been obtained (Table 4).

Table 4. Ranking of the alternatives.

Toy Box	Containerised Units	Dedicated Structure
0.354	**0.365**	0.280
- 3 %	Ref.	- 23 %

The obtained final ranking indicates that the *Dedicated Structure* concept option can be excluded for the design of the AIM-TU since its score is 23 % lower than the best one. Despite good performance in many criteria, it is heavily penalised against Lowest Initial Resources, Space and Versatility criteria. Hence, the optioneering process highlights that the preference is for lower cost, more flexible AIM-TU concepts which are deployed within existing buildings, such as the RACE workhall.

Regarding the remaining two options, the *Containerised Units* concept has received a small preference (3 % higher) in comparison with the *Toy Box* concept. As the score between these alternatives is very close, neither should be excluded as a viable option. If there was a drive to select a final concept at this stage, different approaches could be taken to resolve the tie. Firstly, the questionnaire could be addressed by a larger panel of experts in order to consider a wider audience and views. Secondly, additional criteria could be added to provide a mechanism to distinguish between the concepts. The ELIGERE platform allows new experts or criteria to be added to the selection process without requiring previous responders to have to repeat the entire questionnaire, and the web-based nature of the tool would make this a simple process. Lastly, the detailed breakdown of the strengths of each concept, shown in Table 3, could be studied to develop a hybrid concept which exploited the advantages of each design.

The strategy adopted here was to take both concepts forward for further development, allowing clearer differences to emerge as the concepts evolved. The result of this work was to finally select the *Toy Box* concept. This was because further exploration deemed that the *Containerised Units* concepts would have led to more difficult integration with the other activities which were scheduled to take place in the RACE workhall at the same time as the AIM-TU installation and commissioning.

The key benefit of the approach proposed in this paper is that it allows a methodical, systematic and transparent approach to reach a decision when quantitative data is not readily available. As decisions taken early in the design stage can have the most impact on the final form of the design, it is crucial that these are tackled in the most robust way possible. A systematic approach such as this allows decision processes to be well documented and iterated in future as the design progresses, giving confidence that design choices are as objective as possible.

5. Conclusion

The SE approach has been become widely adopted in the nuclear fusion technology field. Here, we have illustrated how MCDM methods can provide design teams a powerful tool to make informed design choices even at the early stage of the design, when quantitative data is typically not available and so designs must be guided primarily by expert experience and judgement.

In the framework of the EUROfusion R&D activities related to the design of the DEMO reactor, automating remote maintenance procedures plays a pivotal role, as this is key to achieving the commercially-relevant plant availability which DEMO must demonstrate. To understand the feasibility of automated maintenance, as well as quantify its benefits and limitations with a high level of confidence, a dedicated test platform is needed. Thus, the AIM-TU is being developed at the UK Atomic Energy Authority.

In order to select the design concept on which the AIM-TU facility will be based, a SE approach integrated with MCDM methods has been used. Starting from the capture of the stakeholder requirements, a set of 10 evaluation criteria was established to select the best option among three proposed concepts for the AIM-TU design.

The ELIGERE platform, a web-based questionnaire implementation and solver engine for the FAHP MCDM method, was used in this study. The use of a fuzzy logic approach means that the high levels of uncertainty inherent in an early design phase can be coped with consistently. A panel of experts conducted the pairwise comparison of criteria to establish their relative weighting, and then applied those criteria to evaluate each of the design alternatives. The use of ELIGERE has allowed the experts to address the questionnaire conveniently and individually, avoiding the influence of the other experts' opinion and reducing the duration of the optioneering phase.

For the AIM-TU design the results obtained excluded the *Dedicated Structure* option, identifying that the concept scored poorly against initial costs and flexible space utilisation, which proved to be important metrics for selection by the experts. The other two options (*Toy Box* and *Containerised Units*) were evaluated as being equally valid, and hence were taken forward for further investigation.

This process eventually led to the selection of the *Toy Box* concept, as the evolution of the designs showed some advantages in its practical integration with other activities scheduled to take place in parallel at the work site.

Acknowledgment

The authors would like to thank the AIM-TU project leader, Richard Gowland, and the other members of the AIM-TU project team (Emil Jonasson and Guy Burroughes) for their kind collaboration. Authors also thank the other members of the evaluation panel (Oliver Crofts, Jessica Korzeniowska, Antony Loving, David Middleton-Gear and Neill Young) for their availability.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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