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Spaceship Earth. Space-driven technologies and systems for sustainability on ground ☆

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ABSTRACT

As awareness towards the problem is growing, eco-friendliness is today a paramount requirement for all space activities and in particular for the ground segment, fully comparable to other industrial sectors. The present work focuses on the assessment and the sustainable development enhancement of a ground-based space facility, the European Astronaut Centre (EAC), located in Germany. The project is framed within the European Space Agency development of an environmental outlook, which aims not only at the full compliance with the legislation and at assessing the impact of its activities, but also at laying the foundation for future evolution through innovation. Indeed, ESA promotes the sustainable use of space as a necessity and duty for Europe. As history teaches us, technical knowledge emerged within the space sector serves as innovation driver in other industrial branches: the goal of the project is to transform the EAC building into a spaceship integrated with the territory through the conscious management of this spontaneous process, fostering the combination between the space sector and the architecture and civil engineering fields. The work explores the potential of space technologies, processes and systems applied on ground and presents a range of space-driven innovative concepts which may improve the sustainability of the EAC building, focusing on different aspects of its resource demand – energy, water and waste management – and defining the integration with the pre-existing compound, the limitation of the impact on the surrounding landscape and the participation of the local community as additional fundamental requirements. Indeed, the project embraces the full concept of sustainability, which considers not only eco-friendliness but also its balance with economic and social aspects. Two factors – a certain urgency for action, which leaves little space for research and experimentation, and a call for ground-breaking solutions – guided the design activity: taking advantage of these conflicting requirements, a comparison between standard technologies and innovative space-related concepts was performed. When dealing with complex and uncertain scenarios, decision among the possible solutions is not straightforward and needs to be supported by appropriate

Abbreviation: AHP, Analytical Hierarchy Process; EAC, European Astronaut Center; ESA, European Space Agency; FC, Fuel cells; GHG, Greenhouse gas; ICE, Internal Combustion Engines; IPV, Innovative Photovoltaic; LCA, Life Cycle Assessment; MCFC, Molten carbonate fuel cell; MGT, Micro Gas Turbine; MRC, Microbial fuel cell; NMV, No-Mix vacuum toilet; O&M, Operations and Maintenance; PAFC, Phosphoric acid fuel cell; PEMFC, Proton exchange membrane fuel cell; PV, Photovoltaic; R&D, Research and Development; SOFC, Solid oxide fuel cell; SPV, Standard Photovoltaic; TRL, Technology Readiness Level

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methodologies: a multi-criteria and quantitative decision-making tool, able to concentrate on the main goal while considering all other relevant aspects – environmental, economic, social sustainability – was therefore developed. Furthermore, the project promotes local community participation in the decisional process, as a way to enhance knowledge, generate understanding and promote towards the EAC redesign, space activities and their potential innovative impact on sustainability.

1. Introduction

Nowadays sustainability is an essential requirement for all industrial activities, both from a social corporate responsibility and from a regulatory compliance point of view. The space sector in the past has shown a lack of commitment in this sense, both in terms of environmental footprint reduction and in impact monitoring. Up to now, the space industry is still implementing insufficient analysis on the environmental impact of its activities. This project aims at filling this gap towards the current perspective of sustainability by focusing on the space activities on ground.

This main challenge is framed within the European Space Agency (ESA) development of an environmental outlook, aimed at the full compliance with the legislation and at the assessment of the impact of its activities. ESA commits to become an exemplary space agency by promoting the sustainable use of space as a necessity and a duty for Europe. Action is necessary to turn a threat into an opportunity. Keeping in mind the peculiarities of space operations – the only anthropogenic activities which cross all layers of the atmosphere we concentrate on the definition and implementation of design procedures suitable to minimize the environmental impact of space assets on ground. Furthermore, in order to enhance its innovative potential, the project fosters a contamination between the space sector and other industrial areas as a starting point for the design activity. Even focusing on different design targets, outer space assets and on-ground activities, a common goal may exist: the development of resource efficient processes and technologies which might reduce raw material inputs, energy consumption, waste and costs.

Within this framework, our work focuses on the assessment and the sustainable development enhancement of a ground-based space facility. In particular it has been decided to use as a case study the European Astronaut Centre (EAC) in Köln, Germany. The EAC has been approached as a spaceship on Earth, requiring at the same time innovative and sustainable technologies. This definition covers both cardinal aspects of our design activity: the definition of space-driven concepts for the EAC redesign and the environmental advancement goal of the project.

1.1. Requirements definition

The EAC buildings provide training facilities to the astronauts and include offices, meeting rooms, training areas and a swimming pool as well. All these elements require a high energy and water demand and produce a large amount of waste. Their management acquires high importance from an environmental perspective, and becomes the key for sustainability improvement. EAC, unlike many ground-based space sites, is not located in a deserted area but near a city: accordingly we identified the integration with the pre-existing compound and the attenuation of the impact on landscape and local community as additional fundamental requirements.

Indeed, our design activity began with the broadening of the environmental advancement objective in order to fully embrace the concept of sustainability, considering not only eco-friendliness but also its balance with economic and social aspects.

In collaboration with ESA partners we structured our tasks as follows:

- The sustainability assessment of the EAC by the ecology point of view.
- The undertaking of a design process within a technical context, namely the exploration of the potential of space technologies applied in the architecture and civil engineering fields.
- The generation of space-driven innovative concepts which may turn the EAC into an “Environmental Advancement Centre”, namely a first attempt to enhance sustainability through space technologies, processes and systems. The extreme performances, limited resources and strong constraints that characterize the outer space environment are regarded as design opportunities, inspiration and sources of innovation for the ground segment.
- The definition of a decision-making process for the evaluation and comparison of the concepts developed. The tool requires flexibility in the criteria definition and needs to consider technological, economic and social aspects.

1.2. Exploring the opportunities

As a second step, we tried to identify the most relevant limitations and constraints of the project. This process allowed us to highlight several opportunities for innovation. Taking on this perspective, we pinpointed the most relevant ones:

- The EAC building, far from being space-specific, supports the development and testing of concepts that are potentially applicable to the standard construction industry.
- The EAC location enables the experimentation of the

Nomenclature

Symbols

C	Cost
CR	Consistency ratio
D	Durability
E	Economic feasibility
M	Maturity of the technology
OPM	Option Performance Matrix
R	Reliability
RVV	Relative Value Vector
S	Degree of sustainability
VFM	Value for money

integration between its facilities and the local community, as an opportunity to enhance the perception of space activities, their role in innovation and their potential positive impact on sustainability.

- The complex decision-making process, which requires an ad hoc tool and includes sustainability as a crucial criterion, may foster a paradigm shift in assessment procedures. In addition, experimenting openness and community involvement may enhance consensus towards space activities, a critical resource for ESA [1–3].
- The support from ESA allows a potential implementation of the concepts, thanks to the agency ownership of technologies, expertise in the field and budget management experience, which may control the high costs of such an investment and drive the competitiveness of Europe through sustainability.

1.3. Decision-making process

At the end of the project we obtained a range of feasible solutions to improve the EAC sustainability, each of them displaying some pros and cons. We had to choose the "best" option available but this decisional process was not straightforward without a clearly dominant technology. We consequently thought important to define an ad hoc assessment tool for our design proposals: we relied on the Analytical Hierarchy Process (AHP), developed by Thomas Saaty in 1980 [4–6].

The peculiarities of our project fulfill the AHP application requirements which are basically the availability of alternatives and the absence of a clear criterion for their evaluation. As concerns the selective criteria we decided for a compromise between complexity and completeness, identifying the most relevant as follows:

- The degree of sustainability (S), which refers to the technology overall contribution to sustainability and represents a necessary but not sufficient index in relation to requirements.
- The maturity of the technology (M), a parameter in open contrast with "S" if we consider that innovative solutions are often experimental and yet not suitable for large scale applications. The importance of balancing the oppositions through the AHP method is evident.
- The economic feasibility (E), in opposition to "S" but concordant with "M", since mature technologies are likely to be economically competitive.

The AHP process outcome is a quantitative assessment and a mathematical rigorous ranking of our design alternatives. The ESA approved this approach as the AHP is considered a valuable tool for decision making practices in complex and uncertain contexts.

2. Solutions development

In accordance with the project requirements we identified the following areas of intervention:

- Energy solutions;
- water management;
- waste management;
- preservation of local area.

2.1. Energy solutions

The analysis of the above-mentioned fields considered the technology state of the art and its current application at the EAC. We also studied the related space technologies, as groundwork for the generation of innovative concepts. Finally we performed a comparison between standard technologies and innovative space-related concepts.

As regards the energy field, we began with the data provided by ESA in the EAC building map, as well as its fossil fuels consumption in the last few years. From this information, we found that about 10% of the total electricity consumption and 100% of the heat demand were supplied by the power plant of German Aerospace Centre, located close to EAC. Hence, still 90% of the total electricity is supplied from the external grid.

Based on this data we were able to perform a state of the art analysis and derive the energy consumption levels of the base, both in terms of final energy uses and of primary sources. In 2011, the EAC electricity consumption was about 1270 MWh, while the energy consumption for heating was about 1900 MWh.

According to such impressive figures we can expect that investments devoted to the local energy production and energy efficiency will be very profitable, not only because of the high return in terms of energy savings, but also because such an implementation can meet economies of scale in the costs of the plants. From a qualitative perspective, we can see that the EAC energy is not based on renewable or sustainable resources, since almost all the internal demand for heat and power was satisfied externally by purchasing the energetic vectors from the electrical and gas grids. Accordingly, we decided that the best way to intervene was to develop solutions for the sustainable supply of electric energy and heat. Sustainability in this sense may be obtained by following two different design trends: energy efficiency and renewable energy production. We developed solutions based on renewable plants for the power production, i.e. photovoltaic (PV) plants and wind turbines. Besides we also proposed cogenerative heat and power systems, such as Internal Combustion Engines (ICE), Micro Gas Turbine (MGT) and fuel cells (FC), for a more rational energy use. In both cases we proposed also "space inspired" solutions, namely the innovative photovoltaic technology (IPV) and the fuel cells, underlying their pros and cons with respect to the other "standard solutions". It is worth to note that ICE and MGT technologies make use of fossil fuels to produce electricity and accordingly cannot be classified as "green" in strict terms. However, a smart cogenerative application of these solutions, with the production of both heat and power, permits us to reduce the overall primary energy consumption and improves sustainability in wider terms.

In summary, for the design and installation of wind turbines we performed a technical analysis to calculate the yearly electrical productivity. We found that there exists a model of turbine that can produce around 5.22 GWh per year, considering that the Köln area is interested by a medium-strong wind with an average speed of 3.5–5 m/s and a nominal power of 50–150 W/m^2 [7]. With the EAC consumption being 1270 MWh in 2011, the plant will definitely provide all the needed energy, which is the 24% of the total production. The remaining 76% of the production could potentially satisfy the German Aerospace Centre need for energy, besides being sold to the external grid.

As regards the PV plants and the possible benefits from solar energy, the global horizontal irradiation map of the area near Köln was checked [8]. According to this map, the energy productivity is quite low, with a value around 1100 kWh/m^2 per year. Since the electricity demand of EAC is of 1270 MWh, considering an average efficiency of the plant (solar to electricity) around 15% and a value for the irradiance of 1100 kWh/m^2 per year, we can estimate that the solar field must have an area of about 7700 m^2 for standard PV technologies (SPV) like thin film or crystalline Si.

For innovative PV technologies (IPV), the most promising and practical solutions are the multi-junction and the thin film cells, which work with different semi-conducting materials [9,10]. PV innovative solutions have higher energy production efficiency of about 30% compared with that of standard ones with 15%. Hence, they can be adopted to improve the EAC sustainability: their environmental impact is comparable to the standard PV solutions in terms of space use and aesthetic impact.

The other main aspects to be considered are the cost, the maturity of the technology and the energetic sustainability improvement. Certainly, these new technologies are more costly and less reliable. On the contrary they permit a greater contribution to the sustainability thanks to their superior performances.

Cogeneration is the combined production of heat and power from the same primary energy input. In this sense any power device can turn into a cogenerative machine provided that heat is not discharged into the environment and is used to satisfy a thermal demand from a user. The interesting aspect is that heat recovery generally implies a reduction in the use of primary energy, which grows as the total efficiency of the cogenerator rises. For this reason cogeneration is considered an efficient and sustainable practice.

The internal combustion engine (ICE) is the most used technology for small cogenerative plants. Being derived from the automotive industry without major changes it offers high levels of reliability and durability [11]. To give an example of sizing and choosing of an ICE suitable for the EAC base, we can assume reasonably 8000 equivalent working hours for the device, given its high reliability. To satisfy the electric energy demand of 1270 MWh in 2011, we require an engine of 160 kWel; whereas considering the thermal loads of 1900 MWh we find 237.5 kWth. According to the ICE solutions available on the market the specific cost is about 1000 €/kW in the range 100–300 kW, while the electric efficiency is about 33–34%. Moreover the O&M costs decrease significantly with the size of the machine [12]. Finally we can expect a thermal efficiency up to 55% since the thermal loads of EAC are below 100 °C (typical service building demand) and therefore it is possible to recover heat both from flue gases and from the inter cooler, oil and cooling systems. The Micro Gas Turbine (MGT) constitutes a valid alternative to the ICE technology as the required size of the prime mover grows. The micro-turbine is sensibly different from the standard gas-turbine, which is not generally used below the threshold of 3 MW of electric power. The reason is that the specific cost in €/kW tends to grow, while the efficiency diminishes as the nominal electric power decreases. As a consequence in the small size plants the whole design of the system is changed when adopting micro-turbines [13]. As we did for the ICE, we can assume reasonably 8000 h equivalent per year. So again the nominal electric power of the MGT is in the range 150–250 kW. We studied commercial solutions by the most important manufacturers of micro-turbines and observed that the electrical efficiency is stable around 33% in the range of interest for EAC, while the total efficiency is above 80% because of the low temperature heat recovery from the exhaust gases [14,15]. The specific cost can be estimated starting from 1100 €/kW, down to 900 €/kW for the biggest sizes. Finally we can assume a maintenance cost of about 0.015 €/kWh.

The fuel cell (FC) is a device which permits the oxidation of gaseous reactants, producing electrical power and discharging heat power. This conversion happens without direct combustion, but through electrochemical reactions of oxidation and reduction. As a result the ideal efficiency of the fuel cell can be higher than any other power device based on the conversion of the fuel into heat through common combustion.

There are different models of FC, depending on the electrolyte adopted and consequently on the reactions, reactants, ions and performances. FCs are available in different types, such as SOFC, PEMFC, PAFC, and MCFC [16]. In this context SOFC stands for "Solid Oxides" electrolyte, PEM for "Polymeric Membrane", PA for "Phosphoric Acid" and finally MC for "Molten Carbonates". Given the high electrical efficiency, heat recovery, modularity, compactness and absence of pollutants, the FC would be a perfect device for a generated distribution application alike the EAC. Actually its diffusion is being prevented by strong limitations in terms of investment costs and maintenance, life expectancy and reliability [17]. Each model has different performances and works at a different level of temperature. Anyway a common trait between them is the necessity to feed the anode with pure hydrogen or a syngas, and the cathode with a mixture of oxygen and carbon dioxide.

2.2. Water management

Considering the water management of EAC, the preliminary phases of research and the analysis of water consumption data pointed out the importance of water management techniques in proposing sustainable solutions with the aim of greening a building.

After performing an in-depth analysis of the water management system of EAC, as in Table 1, we found that noticeable amount of water is consumed by toilet and urinal flushes. Hence, we decided to develop standard solutions to save water consumed for flushing and we found that, by introducing two different types of water efficient toilets (namely composting toilet [18] and No-Mix vacuum toilet (NMV) [19,20]), it is possible to reduce about 40% of the yearly global water consumption in EAC. For instance normal toilets require 6 l of water per flush, while with composting and NMV solutions the amount of consumed water is estimated to be less than 1 l per use [18,20]. In addition, it is viable to use the generated biogas in molten carbonate fuel cells (MCFCs) resulting in a sustainable energy production process.

Subsequently, we proposed fuel cells as a new water source; the concept is inspired by their use in space shuttles for simultaneous water and energy production [21,22]. Various types of fuel cells were analyzed: PEMFC, MCFC, SOFC, regenerative fuel cells and finally microbial fuel cells. In summary, by installing a 150 kW PEM fuel cell it is possible to provide EAC with a part of its required energy and at the same time to generate about 394 m^3 of water in a year, which is 38% of the EAC's yearly water consumption.

We also realized that there is a type of molten carbonate fuel cells, DCF300 [23], which can fully satisfy the electricity and heat needs of EAC. It is also mentionable that this type of fuel cell is able to be fueled with renewable biogas that could be obtained from waste water recovery process in composting toilets and even from the nearby farms activities. Moreover, we introduced microbial fuel cells (MRCs) [24,25] as an innovative solution which allows us to treat water and generate energy at the same time. In future, they can help us to reduce the costs due to waste water treatment by producing electricity on site to power the plant's operating equipment. However, the time required to fully develop these relatively new technologies depends on the investment at stake and on the quality of research.

2.3. Waste management

Identified as a fundamental requirement for sustainability improvement, the waste management area of intervention presents peculiar characteristics in comparison with energy and water fields. In order to develop relevant sustainable solutions, it was necessary to carry out an in-depth analysis of the German and space contexts with respect to waste management. Only in this way we were able to identify the peculiarities of the topic and accordingly adapt our design concept and project perspective.

Based on the data available for recycling of municipal waste [26], Germany is a highly efficient country in terms of waste management. Indeed, in the 2008–2009 period 50–100% of the municipal solid waste was recycled, an impressive figure if we consider the impact this achievement has on the economy and the environment. These figures are likely to increase in the future. In addition, waste management improvement strongly enhances sustainability. For instance, in Germany, it resulted in a relevant decrease in Greenhouse gases (GHG) emissions related to municipal solid waste production [26]. Hence, we can conclude that the EAC building, being interconnected with this highly efficient and historically innovative system, should not concentrate on the development of its own technologies for waste management. Instead, a more advisable strategy may be to improve the quality and decrease the quantity of the waste that is inserted in this network. As a consequence, we did not aim to develop technological concepts, but to provide simple and space-inspired guidelines. Actually the high constraints of the space environment enhanced sustainable practices and behaviors that may also become relevant on ground. These guidelines may be employed by EAC workers and visitors without excessive effort. In accordance with our research

Table 1
EAC equipment estimation of water consumption.

Equipment	Water consumption per use (l)	Frequency per day	Total m^3 per year	Share%
Toilet Flush	9	160	374.4	36
Urinal Flush	6	140	218.4	21
Shower	100	9	234	23
Kitchen Taps	4	100	104	10
Hand Washing	1	300	78	8
Dishwasher	50	2	26	3
Drinking Fountains	0.5	100	13	1
Laundry Machine	60	0.2	3.12	0.3
Total			1037.92	100

and analysis about the German and space contexts, we defined the following guidelines for the EAC building waste management improvement:

- *Reuse available material and resources*: in a building like the EAC, in particular in the office area, there are many mistakes such as redundant printing and waste of paper sheets for notes.
- *Reduce waste sources*: as an example for the development of this concept, ESA may provide every employee with a personal completely recyclable aluminum bottle and/or ceramic mug.
- *Recover resources to maximize their efficiency*: for instance, EAC could collect waste water from sanitary systems (e.g. basin, shower, kitchen sink) and use it for water lower quality final uses, such as toilet flushing or irrigation.
- *Recycle products at the end of the cycle*: in favor of recyclable materials.

2.4. Preservation of local area

Preservation of local area was considered mainly for the energy solutions as they can drastically change the surrounding environment. Hence, we evaluated the potential impacts that each solution may have on the local environment.

Regarding wind turbine, its visual impact, noise and the effect on birds and other species were investigated. It was noted that all these problems mainly depend on the size of the wind farm. As in our case the impact concerns just one wind turbine the negative effects are negligible.

Unlike the wind turbine, the environmental impact due to the PV technology is not concerning in terms of noise and biodiversity. On the contrary, the impact should be quantified in a LCA (Life Cycle Assessment) framework considering different factors: land use, energy use and greenhouse gases emissions. Nevertheless, this study takes into consideration only the first factor because considering the small extent of the solar field, the greenhouse gases and the energy use are less important if compared to the visual and aesthetic impact of the panels.

The use of land depends on the panels location and on the dimensions of the entire photovoltaic plant. Usually large scale facilities have a great visual impact on the environment and raise concerns about land degradation and habitat loss. However in our project, thanks to the small scale of the solar park, we will be using only a portion of the land (considering that part of the panels would be placed on the walkable roof). Actually we noticed that almost half of the panels can be installed on the roofs, significantly decreasing the visual impact.

3. Decision making: AHP

When dealing with complex and uncertain scenarios, decision among the possible solutions is not straightforward and needs to be supported by appropriate methodologies. Accordingly we adopted a multi-criteria and quantitative decision-making tool, able to focus on the main goal while considering all other relevant aspects: environmental, economic and social sustainability. If the concepts development phase represents a first guideline for space activities' sustainable development on ground, this second project output provides a conceptual methodology that may be applied also within different decisional context.

In the previous sections we proposed a range of solutions, some of them intended as "standard" (based on mature technologies), while others considered innovative (as applications from the space sector). Each of those many alternatives at disposal displays some pros and cons with respect to the others. In the end, though, we have to propose just one or two solutions, at most, for each field of interest. To do so, we need to select the "best" solutions between the ones found. This decision process is not straightforward, because there is not a clearly dominant solution and even the selective criterion to be used is unclear. We need a method which could help us to find both the most suitable solutions and the proper selection method to apply for the decision process.

We decided to use the Analytic Hierarchy Process (AHP), developed by Thomas Saaty in 1980 [5,6]. At the end of the selection process we will be able to rank the alternatives in a quantitative way.

3.1. Decision making tool description

The AHP is a quantitative method which uses numbers to make comparisons between alternatives to be ranked and criteria to be used for the ranking. Let us suppose having some solutions for a given problem, while we do not know which is the best to select. To make this choice we consider different selective criteria, such as Cost (C), Reliability (R) and durability (D). The first problem is that we do not know the relative importance of these criteria: which is the dominant aspect to be considered? The AHP solves this problem by building a matrix of pair-wise comparisons between the alternatives. To do so, we can use values like in Table 2 with their relative meaning [4].

For instance if C is much more important than R, we will put the value 5 in the cell on the row of C and the column of R (see Fig. 1). At the same time we must put the value 1/5 for the opposite comparison R vs. C. Of course on the diagonal of the matrix there are all "1" because any option has the equal importance towards itself.

In this way we obtain a matrix called "Overall Preference Matrix" as shown in Fig. 1. By calculating the normalized eigenvector of the Overall Preference Matrix we retrieve the Relative Value Vector (RVV), whose values express the relative importance of the selective criteria [6]. For instance, in this case the RVV is (0.36 0.1 0.54). By looking at the vector we can conclude that durability is the most important criterion (0.54), while Reliability (0.1) the less relevant one.

After that, we build new matrices applying the same method already described but using the alternative solutions instead of the criteria. For example, if we have three available solutions X, Y and Z we will build third order matrices. We need to produce each matrix by referring to one of the criteria. In this case the matrices obtained are classified as "Option Performance Matrix". So, in the first matrix we shall compare the relative dominance of the

Table 2
Definition of the values to be used for the comparisons in the AHP technique.

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgment slightly favor one over the other
5	Much more important	Experience and judgment slightly favor one over the other
7	Very much more important	Experience and judgment very strongly favor one over the other. Its importance is demonstrated in practice
9	Absolutely more important	The evidence favoring one over the other is of the highest possible validity
2, 4, 6, 8	Intermediate values	When compromise is needed

	C	R	D
C	1	5	1/2
R	1/5	1	1/4
D	2	4	1

Fig. 1. Overall Preference Matrix derived for the ranking of the selective criteria.

	X	Y	Z
X	1	3	1/5
Y	1/3	1	1/9
Z	5	9	1

	X	Y	Z
X	1	2	1/7
Y	1/2	1	1
Z	7	1	1

	X	Y	Z
X	1	1/3	6
Y	3	1	1/4
Z	1/6	4	1

Fig. 2. Matrix for the ranking of the alternative solutions.

	C	R	D
X	0,18	0,2	0,41
Y	0,07	0,24	0,3
Z	0,75	0,57	0,29

OPM	C	R	D
X	0,18	0,20	0,41
Y	0,07	0,24	0,30
Z	0,75	0,57	0,29

Fig. 3. Eigenvectors for the alternatives and the Option Performance Matrix.

OPM	C	R	D
X	0,18	0,20	0,41
Y	0,07	0,24	0,30
Z	0,75	0,57	0,29

RVV
0,36
0,10
0,54

VFM
0,31
0,21
0,48

Fig. 4. Example of multiplication between OPM and RVV to obtain VFM.

alternatives with respect to their cost (C), in the second to R and in the last one to D. We report the resulting three matrices in Fig. 2. For each matrix we find the eigenvectors, whose values give a ranking between X, Y and Z with respect to the criterion used for the comparisons. Then the vectors are put together as columns of a new matrix called "Option Performance Matrix" (OPM). This simple procedure is shown in Fig. 3. Basically the first column of the OPM matrix is given by the eigenvector of the first matrix in Fig. 2, and so on. In practice each column of the OPM shows the hierarchy of the solutions for each criterion: for example we can see that X is the best alternative for durability (0.41), while the worst for reliability (0.2).

Subsequently, it is required to combine the ranking given to the solutions (OPM) with the one given to the criteria (RVV). To do this the AHP requires a simple product between the OPM and the RVV, which gives a final vector called Value For Money (VFM): OPM$*$RVV$=$VFM (see Fig. 4). The VFM represents the final evaluation of the alternatives: we found that Z is the best (0.48) and X the worst (0.31).

Finally, we need to verify that the results obtained are valid. To do this we must compute for each matrix an indicator called Consistency Ratio (CR). The CR is a number which measures the consistency of the judgments made for each class of comparisons. A matrix is acceptable only if its CR value is below 0.1. For instance if the CR of the Overall Preference Matrix is 0.2 (then above 0.1) the matrix is not acceptable and it must be modified. In other terms the judgments made to build that matrix are not coherent and therefore the results given by the AHP would be pointless. For the sake of brevity we do not explain in detail the procedure to follow to retrieve the CR [4].

3.2. AHP in practice

3.2.1. Criteria selection

The first step required by the AHP method involves the choice of the selective criteria to be adopted in the decision making process. We decided to choose three main criteria, as a compromise between complexity and completeness. The first criterion chosen is the "degree of sustainability" (S): it indicates the overall contribution to sustainability given by the technology. For example, in the energy field the criterion "S" regards the lowering of emissions, the production of clean energy and the reduction of primary energy use (i.e. Kyoto targets). We can expect that the "degree of sustainability" will be the most important criterion as it includes the main targets of the project. Anyway "*S*" is not exhaustive for a proper selection of the best ideas: a second criterion to be considered is the "maturity" of the technology (*M*). Actually "*M*" is in open contrast with "*S*", because innovative technologies are developed to provide improvements in terms of sustainability but often they are just experimental and not ready for large scale application. This statement underlines the importance of the AHP method which helps us in balancing the oppositions and in finding the best alternative.

The maturity of a technology is a key issue in the space sector where it affects feasibility, cost and the success of a mission. For this reason an indicator called "Technology Readiness Level (TRL)" has been developed: it measures the maturity of each technology on the basis of a quantitative scale from 1 to 9. We decided to make use of the TRL developed by ESA [27]. Table 3 shows the ESA scale adopted.

The third aspect we considered is the "economic feasibility" of a solution (*E*). Also in this case there is an evident contrast with the first criterion, in fact the most innovative technologies (namely good "*S*") are also the most costly (poor "*E*") because of research costs and absence of economies of scale. On the contrary, criteria "*M*" and "*E*" are concordant since a mature technology (namely high "*M*") is likely to be cheap as well, because of economies of scale and learning. We expect that the last criterion proposed will be slightly less important than the others, since the final goal of the project is the improvement of sustainability even without a clear profitability. At any rate cost controlling is very relevant in the space sector and therefore even a single expensive technology could raise some concern. Accordingly we decided to include the criterion "*E*" to AHP in order to avoid choosing good solutions in terms of "*S*" and "*M*" but requiring unaffordable expenditures.

Fig. 5 shows the OPM obtained by the pair-wise comparison of the defined criteria "*S*", "*M*" and "*E*": the assessment of their relative intensity of importance resulted in the values of the matrix. For instance we observe that *S* is much more important than *R*, since we find the value "5" in the corresponding cell. The RVV obtained proves that *S* is the most important criterion (0.73), followed by *M* (0.19) and *E* (0.08). In particular *E* has a very low weight value, as expected. The Consistency Ratio obtained is 0.06 and then the results are acceptable.

3.2.2. Solutions selection

This second step of the AHP will enable us to select and assess all the options available, finally finding the best ones. In order to apply the method, first we need to classify all the solutions into main groups according to the technology. For instance we will divide all the solutions based on the use of solar energy into "standard photovoltaic" (SPV) and "innovative photovoltaic" (IPV). This preliminary clustering is needed as a trade-off between complexity and precision of AHP: the number of alternatives taken into account is equal to the order of the matrices obtained. So if we used all the solutions the method would be rather complex to manage (even if more precise), because we would have to handle too big matrices.

As a consequence we decided to use six categories in total. Besides SPV and IPV already mentioned, we introduced the "wind power" (W), "internal combustion engine" (ICE), "micro gas-turbine" (MGT) and finally the "fuel cell" (FC). Accordingly we will build 6th order square matrices, one for each criterion (*S*, *M* and *E*) for a total of three. Fig. 6 shows these matrices displaying all the judgments used for the comparisons between the alternatives. In all cases the Consistency Ratio is below 0.1, meaning that the results obtained are reasonable. With the eigenvectors of each matrix we can build the OPM matrix reported in the following figure. We notice that the most mature technologies are also the less expensive, while the most "sustainable" options are also the less mature and cheap. These results are coherent with the premises of the judgment.

3.2.3. Final ranking

Finally we can calculate the "Value For Money" vector by multiplying OPM and RVV. This vector represents the final result of AHP, weighting the judgments in the OPM with respect to the criteria in the RVV (see Fig. 7). By looking at the figures in the VFM we conclude that the best solution would be the wind turbine "W", followed by solar energy "IPV" and "SPV". On the other hand the worst

Table 3
Technology Readiness Levels in the European Space Agency (ESA) [27].

ESA Technology Readiness Level (TRL) summary	
TRL	**Level description**
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical & experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
7	System prototype demonstration in a space environment
8	Actual system completed and "Flight qualified" through test and demonstration (ground or space)
9	Actual system "Flight proven" through successful mission operations

	S	M	E
S	1	5	7
M	1/5	1	3
E	1/7	1/3	1

→

RVV
0,73
0,19
0,08

Fig. 5. OPM matrix and relative RVV vector.

S	SPV	IPV	W	ICE	MTG	FC
SPV	1	1/5	1/3	3	3	3
IPV	5	1	1/5	5	5	5
W	3	5	1	9	9	5
ICE	1/3	1/5	1/9	1	1	1/3
MTG	1/3	1/5	1/9	1	1	1/3
FC	1/3	1/5	1/5	3	3	1

M	SPV	IPV	W	ICE	MTG	FC
SPV	1	5	3	1	3	7
IPV	1/5	1	1/7	1/5	1/5	3
W	1/3	7	1	1/3	3	5
ICE	1	5	3	1	3	7
MTG	1/3	5	1/3	1/3	1	7
FC	1/7	1/3	1/5	1/7	1/7	1

E	SPV	IPV	W	ICE	MTG	FC
SPV	1	3	1/3	1/5	1/5	5
IPV	1/3	1	1/5	1/7	1/7	3
W	3	5	1	1/3	1/3	7
ICE	5	7	3	1	1	9
MTG	5	7	3	1	1	9
FC	1/5	1/3	1/7	1/9	1/9	1

Fig. 6. Matrices and eigenvectors for the solutions selection (criteria "*S*", "*M*" and "*E*").

OPM	S	M	E
SPV	0,12	0,31	0,08
IPV	0,25	0,05	0,04
W	0,47	0,18	0,16
ICE	0,04	0,31	0,34
MTG	0,04	0,12	0,34
FC	0,08	0,03	0,02

×

RVV
0,73
0,19
0,08

=

VFM
0,15
0,19
0,39
0,12
0,08
0,06

Fig. 7. OPM matrix and RVV vector multiplied to obtain the VFM vector.

option is the fuel cell "FC", along with the other technologies namely "MGT" and "ICE".

4. Conclusions and final remarks

Taking into account both the main project goal (the development of a sustainability model for ESA) and the self-defined requirements (the generation of a range of concepts) we adopted a flexible approach towards the problem, providing useful guidelines for EAC redesign and sustainability level improvement. As a result this model may also be applied to other case studies or similar projects, thanks to the flexibility of the "space-driven" concept and of the decisional tool.

To sum up, the project followed the typical steps of a design process:

- *State of the art analysis*: The data and information researched and provided by the ESA were used to assess the EAC in qualitative and quantitative terms. Thanks to the preliminary study we were able to define energy, water and waste management as relevant fields of intervention: we needed to study and develop effective innovative solutions within these three main topics. During the process it became apparent that there was a different aspect of sustainability to consider, namely the social impact of the EAC in respect of local inhabitants.
- *Development of the solutions*: The preliminary state of the art analysis allowed us to build a common knowledge base and to understand constraints and opportunities as regards space technologies, users, stakeholders, environment and EAC pre-existing facilities. Accordingly, we developed a range of solutions targeted to some specific aspects of the sustainability for the EAC, within our identified areas of intervention. This work involved both a theoretical analysis and a contextualization with respect to the state of the art. Afterwards, we designed and sized each solution, taking care of the particular requirements of the building. Where relevant, we assessed the environmental impact of our interventions on the Astronaut Centre and on the near city of Köln.

- *Selection of the solutions*: In this step of the project we addressed the need of assessment and choice among the developed range of solutions. Firstly, it was necessary to understand upon which criteria we should consider a given solution "better" (as in more respondent to the requirements) than another. We therefore defined the relevant criteria to be applied in order to compare the pros and cons, and to carry out a comparison among the concepts. In each field we found a meaningful trade-off between the cost of the solution, its maturity level and the contribution to sustainability. In particular, it emerged that the so-called "standard solutions" are cheaper and more reliable, while the innovative ones can be considered more sustainable. We solved the conflict between the requirements through the AHP. This tool involves the adoption of a mathematical approach, allowing a ranking of the criteria by their importance. The output is the classification of the alternative solutions, with respect to each of the three considered criteria. As a final result we obtained a ranking of the sustainability concepts, weighted on the relative importance of the criteria. In this way we managed to highlight the best technologies to be applied within each field of interest.

According to the results obtained, we believe that the overall goal of the project has been fulfilled: ESA now appears to be capable of improving the EAC sustainability by applying the selected solutions. In this perspective, we reckon that our careful design and environmental impact assessments will provide useful guidelines to make the process easier. The ESA approved the usefulness of AHP as regards the decision-making tool, which was considered to be useful as a decisional device also in other contexts. In addition, we fulfilled another strong requirement set by ESA: the high innovative level of the proposed solutions. This goal has been achieved by choosing space technologies as a source of inspiration, in addition to standard ones.

The technical solutions developed within the energy, water and waste management sections can be considered as practical output, whilst the decisional methodology represents the theoretical aspect of the project. We believe that this approach is a valuable reference for further projects involving the adoption of space technologies on Earth. The reason is, whenever we want to apply innovative space-driven technologies on-ground, a competition with commonly applied technologies will raise. In order to define the winning alternatives, the criteria that we proposed might be applied. This dilemma could be solved through our approach, which fosters a shift in the common industrial practices. Actually, we do not only consider economic aspects, as we may have done by applying a purely market-based approach. Since our main goal is environmental impact reduction, we cannot define the cheapest option as the best one: the cost of technology becomes less relevant than its reliability and efficacy in reducing pollution and resources consumption.

This revolution in the decisional process could also have a positive outcome in many other industrial fields. Bestowing value to both environment and profit may stimulate the adoption of innovative and efficient technologies, otherwise too expensive. As a consequence, space technologies and concepts might be more intensively applied, fostering R&D processes and enhancing costs abatement through economies of scale.

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